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THE USE OF THE POLAROGRAPH IN THE DETERMINATION OF LEAD IN GASOLINE ENGINE FUEL, LUBRICANTS, AND DEPOSITS*

By R. W. Swanson† and P. H. Daniels†

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THE USE OF THE POLAROGRAPH IN THE DETERMINATION OF LEAD IN GASOLINE ENGINE FUEL, LUBRICANTS, AND DEPOSITS*

By B. W. Swanson † and P. H. Daniels †

Summary

Some polarographic and amperometric titration methods for the determination of lead are discussed, and procedures are described for the determination of lead in gasoline, lubricating oils, engine sludges, and combustion chamber deposits.

Introduction

The universal practice of incorporating tetra-ethyl lead (TEL) in aviation gasoline, and the use of TEL, though in smaller quantities, in automobile gasoline has resulted in a demand for the estimation of lead in the fuels, lubricating oils, and deposits from all types of spark-ignition internal combustion engines. The amount of lead to be estimated may range from very small percentages, or even traces, to lead as a major component, and the sample size may be anything from a few milligrams to many grams. Each of the many chemical methods available tends to cover one specific phase of this work, and to obtain the required accuracy and sensitivity it is often necessary to process large amounts of sample and to resort to long, tedious separations and precipitations. From a careful study of the methods available, the general suitability and accuracy of the polarograph, and in some cases of amperometric titration, have been well established for this determination. Furthermore, as a result of the increased sensitivity of these methods, great reductions in time and materials are possible. In this paper it is proposed to give short accounts of some methods based on the polarographic technique that have been successfully used in the determination of lead in: (1) gasoline, (2) lubricating oil, and (3) engine deposits.

Gasoline

The greatest loss of time in the ordinary chemical method is during the final lead determination, and it seemed possible that by the application of the polarograph at this stage a considerable saving could be achieved. Time saving is of the greatest importance during blending operations at a refinery when lead contents are required to be known quickly.

Two normal methods for the extraction of lead are in common use, one depending upon extracting under reflux with boiling hydrochloric acid, and the other upon cold extraction with a solution of potassium chlorate and sodium chloride in nitric acid (Schwartz reagent). A polarographic method based on a modified hot hydrochloric acid extraction has been recorded by Borup and Levin,[1] but, as the Schwartz reagent extracts the lead very

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rapidly, the possibility of using a polarographic finish to this method was examined.

Provided the copper indicator had been omitted from the Schwartz reagent, the residue obtained when the extract was evaporated to dryness, together with ammonium acetate, gave, in aqueous solution, a good supporting electrolyte for the polarographic determination. Lead waves of good shape were obtained, and maxima were suppressed by the use of acid magenta. The time taken for the whole determination was about 35 minutes, and the sample required was smaller than in the normal procedure.

Method 1 : *Extraction—Polarographic Method*

Extract 20 ml gasoline with three 5-ml portions of Schwartz reagent, shaking each portion for 3 to 5 minutes. Combine the extracts and evaporate to dryness. Add a further 5 ml of reagent and again evaporate to dryness. Dissolve in boiling water (10 ml) and add solid ammonium acetate (5 g). When all salts have dissolved, cool, transfer to a 50-ml standard flask containing magenta solution (0·05 per cent, 20 ml), make up to 50 ml with water. Pour the solution into the polarograph cell and flush with inert gas to remove oxygen. Using a suitable sensitivity, record the polarogram at 25° C over a range of potential −0·3 to −1·0 V versus the internal mercury anode. Lead gives a wave at a half-wave potential of −0·55 V. Calibrate in terms of ml TEL per gallon, using standards of known composition treated in the same manner, and results may then be read directly from the diffusion current.

TABLE I

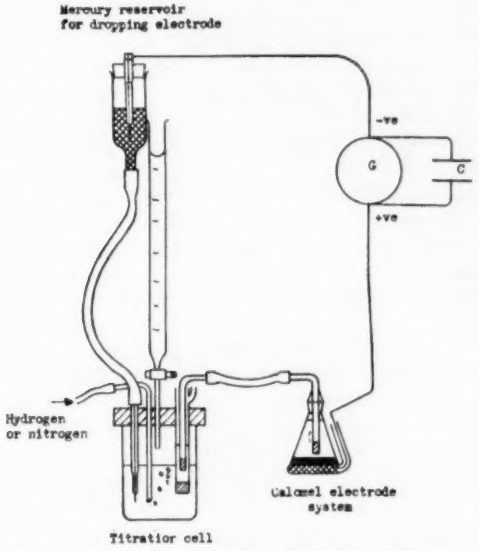
Determination of TEL in Gasoline

Sample	TEL, ml/I.G. at 60° F	
	By IP 116/49 Gravimetric, chromate finish	By IP 116/49 Extraction, polarographic finish
Automobile gasoline :		
1	0·91	0·90
2	2·00	2·04
3	3·34	3·32
Aviation gasoline :		
1	4·02	4·05
2	5·16	5·16
3	7·20	7·18

Table I compares results obtained by this method and the normal gravimetric procedure, and it will be seen that they agree within the repeatability limits (0·04 ml) specified by the IP for the Schwartz method. However, data are not available to decide the magnitude of the reproducibility but, because of the instrumental accuracy of the polarograph, which is normally given as ± 2 per cent, it is to be expected that the reproducibility will be of this order and hence outside the specification limits.

The success of this procedure was somewhat overshadowed by the fact that the apparatus required was expensive and not generally available for routine testing. With amperometric titration the instrumental error is usually less than in direct polarography, and it was known that lead could be determined with a high degree of accuracy by amperometric titration with potassium chromate or dichromate.[2]

Accordingly, the apparatus shown in Fig 1 was assembled. The dropping mercury electrode system was the same as that used in the polarographic method. The calomel electrode was made in a small flask and connected to the titration vessel by an agar–KCl salt bridge with a sleeve tube containing KNO_3 solution. The galvanometer was a Cambridge spot galvanometer of 50 ohms resistance damped with a 4000-μF condenser.



G = galvanometer C = damping condenser

FIG 1

DIAGRAM SHOWING ASSEMBLY OF APPARATUS FOR THE AMPEROMETRIC TITRATION OF LEAD AT ZERO APPLIED POTENTIAL

Method 2 : Extraction—Amperometric Method

Extract 20 ml gasoline with three 10-ml portions of Schwartz reagent. Combine the extracts and evaporate to dryness. After all the nitric acid has been removed, cool, and add sodium acetate (0·1 to 0·2 g), acetic acid (2 to 3 drops), and water (40 ml). Heat until all salts are in solution, cool, and transfer to the titration beaker. Charge the sleeve tube with saturated KNO_3 solution and introduce the electrodes into the solution. Adjust the drop rate to 2 to 3 seconds and pass nitrogen for 30 seconds to mix the solution thoroughly. When the galvanometer becomes steady, adjust the zero setting and titrate with M/100-potassium dichromate solution, using 0·2 to 0·3-ml increments near the end point. Plot the volume of titrant against the galvanometer deflection and determine the equivalence point as shown in Fig 2. Standardize the potassium dichromate solution by titrating against a standard lead solution in the same manner. If the damping condenser does not completely suppress the oscillations of the galvanometer, use a mean value.

The analyses obtained on nine samples of gasoline and gasoline blends are given in Table II, where the results are compared with similar ones obtained by IP 116/49. The repeatability of results is generally well within that required by the standard method, and in most cases the two

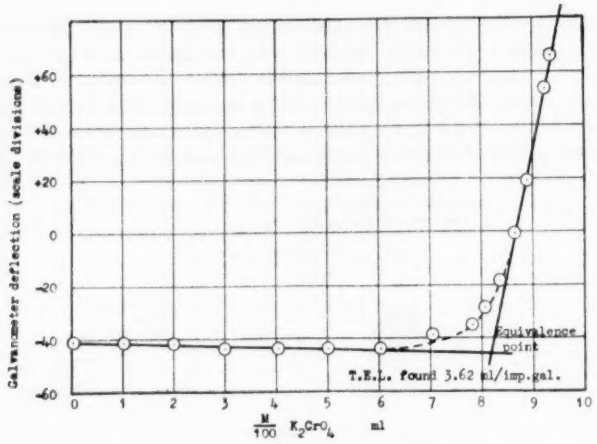


FIG 2

A TYPICAL CURVE FOR THE AMPEROMETRIC TITRATION OF LEAD WITH M/100 K_2CrO_4 IN THE DETERMINATION OF TEL IN GASOLINE

TABLE II

Amperometric Titration Method for the Determination of TEL in Gasoline

Sample	Analysis by IP 116/49 TEL ml/I.G. at 60° F	By amperometric titration	
		TEL ml/I.G. at 60° F	Difference from IP 116/49 TEL ml/I.G.
A	3·63	3·68	+0·05
		3·63	0·00
		3·64	+0·01
		3·62	−0·01
B	1·06	1·03	−0·03
		1·06	0·00
C	5·43	5·41	−0·02
		5·43	0·00
D	7·29	7·32	+0·03
		7·32	+0·03
E	5·43	5·45	+0·02
		5·45	+0·02
F	5·52	5·58	+0·06
		5·59	+0·07
G	5·54	5·48	−0·06
		5·51	−0·03
Blend of 50% C + 50% benzene	2·72 (theoretical)	2·55	−0·17
		2·55	−0·17
Blend of 50% C + 25% benzene + 25% petroleum spirit	2·72 (theoretical)	2·70	−0·02
		2·64	−0·08

methods agree within the reproducibility allowed for IP 116/49. The time required for a single determination was less than 1 hour, and, since the titration is carried out at zero applied potential, the titration assembly is very simple and can be made up from apparatus readily available.

The method described above depended upon extraction of the lead to obtain an aqueous solution suitable for use on the polarograph. Direct polarography has obvious advantages, and other workers have attempted to decompose the TEL *in situ* and then to apply direct polarography, using a suitable solvent to obtain the necessary ionization. A direct method of this type has been described [3] in which the sample is dissolved and the TEL decomposed in anhydrous cellosolve containing hydrochloric acid. This method is applicable to TEL in gasoline in the range 0·5 to 8·0 ml/I.G. and is generally accurate to within ±3 per cent of the lead content of freshly prepared blends. Aged gasolines containing high concentrations of unsaturates and peroxides may give appreciable errors. This factor obviously limits the use of this direct method, and, of course, is not shown by the extraction methods. Furthermore, the time required for a single determination is similar to that required for the extraction polarographic method.

The sensitivity of the polarograph is such that the size of the initial sample is much smaller than that required by the normal gravimetric finish. Although the extraction procedures described require less than half the normal sample, they use a fairly low polarographic sensitivity. The direct method uses only a 3-ml sample, but here again the maximum sensitivity of the polarographic method is not realized. On occasion it has been found desirable to estimate TEL on samples of 0·5 to 1 ml, and the following micro-polarographic procedure has been found to be satisfactory for this purpose.

Method 3 : *Micro-polarographic Method for Lead in Gasoline*

Place 1 to 3 ml of a saturated solution of iodine in carbon tetrachloride in a 125-ml Erlenmeyer flask and then add the sample (0·5 to 1·0 ml). Swirl the mixture a few times and then evaporate the volatile components by gently heating. Tilt the flask and pour off, or remove by a gentle air stream the residual iodine vapours, taking care not to lose any of the sample. Add digestion mixture (9 ml of 3 : 5 : 1 ratio of H_2SO_4,HNO_3,$HClO_4$). Place on a hot plate and boil, swirling occasionally until sulphuric acid vapours are seen to reflux near the mouth of the flask. Remove flask and allow to cool. Cautiously add perchloric acid (0·5 ml, 72 per cent). Re-boil until sulphuric acid again refluxes. Repeat if necessary. Evaporate to dryness.

Add hydrochloric acid (0·3 ml, 12*N*) and water (3 to 5 ml) to the residue. Heat until the salts are dissolved. Add hydroxylamine hydrochloride solution (10 ml, 5 per cent) and boil for 3 min to reduce any iron. Cool and transfer to a 50-ml graduated flask containing gelatin (5 ml, 0·02 per cent solution). Slowly add hydrochloric acid (5 ml, 12*N*) while gently swirling the contents. Dilute to mark and mix well. Using the appropriate sensitivity and a drop rate of 2·5 to 3 sec, record the polarogram over the range −0·2 to −0·7 V. Calibrate against lead standards treated in the same manner.

This method is applicable over the normal range of TEL content, and is generally accurate to within ±3 per cent of the lead content.

Lubricating Oil

Although lead is not as a rule added to engine lubricating oil, the oil quickly becomes contaminated with lead compounds during use in petrol

engines. These lead compounds may be soluble or insoluble. The insoluble compounds, to be considered later, can give rise to engine deposits and sludges. The oil-soluble compounds may be the result of direct contamination by TEL or the results of lead salts of oil oxidation acids dissolving in the oil. Thus, considerable differences in the volatility of the compounds present are possible, and this has a direct bearing upon the method of total lead determination. After careful consideration of many procedures, that based on a wet oxidation of the oil by sulphuric and nitric acids has been found to be the most satisfactory. Only small samples of oil can conveniently be treated by this procedure; consequently, only a small amount of lead is available for the final estimation. Thus, a sensitive procedure is required, and the polarographic method has been shown to be very satisfactory. The method is reasonably rapid, and is suitable for the accurate determination of lead in samples containing barium, tin, iron, copper, aluminium, calcium, zinc, cadmium, sodium, potassium, and phosphorus, in amounts large compared with that of the lead, and vanadium in amounts similar to that of the lead.

Results on samples containing 0·1 per cent or less of lead are obtainable with an actual error of 0·003 per cent or less, while on samples containing 0·1 to 1·6 per cent of lead results are obtainable within ± 3 per cent of the lead present. Typical results are shown in Tables III and IV.

The sample is wet oxidized with sulphuric and nitric acids, and then given a final treatment with $HClO_4$ to oxidize the last traces of organic

TABLE III

The Polarographic Determination of Lead in Oil Containing Other Elements

Oil sample	Elements present, %wt											Lead found, %wt	Error, %wt
	Zn	Ca	Al	Mg	Co	Fe	P	Cu	Ba	Sn	Pb		
1	0·4	0·2	0·05	0·1	0·05	0·1	0·2	0·05	0·2	0·5	0·051	0·051 0·048 0·049 0·051	0 −6 −4 0
2	—	—	—	—	—	—	—	—	—	1·37	0·104	0·102	−2
3	0·05	—	—	0·02	—	—	0·05	0·6	—	—	0·021	0·022 0·021	+5 0
4	—	1·5	—	—	—	—	—	—	—	—	1·56	1·59 1·57	+2 +0·6
5	—	—	—	—	—	—	—	—	0·2	0·5	0·50	0·49 0·50	−2 0
6	—	—	0·2	—	0·6	—	—	0·6	—	—	0·098	0·098 0·099	0 +1

TABLE IV

Polarographic Determination of Lead in Presence of Vanadium

Lead present, mg	Vanadium present, mg	Lead found, mg	Error, %
1·60	10	1·79	+12
1·60	2·2	1·57	− 2

matter. If tin is present, it is removed by volatilization with HBr; the liquid is then evaporated to dryness, the residue dissolved in perchloric acid diluted with water, and iron added. Lead is co-precipitated with ferric hydroxide, the precipitate is filtered off and dissolved in hydrochloric acid. After reduction of the iron with hydroxylamine hydrochloride, the lead is determined on the polarograph.

Method 4 : *Polarographic Determination of Lead in Lubricating Oil*

Arranging that the sample weight shall contain not more than 5 mg of lead, transfer up to 2 g of the sample to a 250-ml beaker and add sulphuric acid (8 to 10 ml, 36*N*) and nitric acid (1 to 2 ml, 16*N*). Cover the beaker with a clock glass and heat until white fumes are evolved. Cautiously add nitric acid (16*N*), drop by drop, to oxidize the organic matter. Again heat until white fumes are evolved, and repeat the addition of nitric acid (16*N*) until a light-coloured solution is obtained.

Cool the liquid slightly and by means of a glass tube with a drawn out end, cautiously add hydrobromic acid (15 ml, 48 per cent), drop by drop, via the lip of the beaker. Control the heating of the beaker so that the liquid boils vigorously throughout the addition, but without such violence as to cause loss by spattering. Continue to heat until white fumes appear.

Cool and add perchloric acid (2 ml, 60 per cent). Heat until the perchloric acid has been driven off and then evaporate to dryness. If any organic matter remains, cool and add perchloric acid (5 ml, 60 per cent). Boil to oxidize the organic matter. Evaporate to dryness; if necessary, repeat the treatment with perchloric acid.

Add perchloric acid to the residue in the beaker (10 ml, 60 per cent) and heat until all the salts are dissolved. Cool, and pour the liquid into a beaker containing hydrochloric acid (20 ml, 6*N*) and ferric chloride solution (1 ml, 6 per cent), stirring well during the transfer. Rinse the first beaker three times with small quantities of hydrochloric acid (6*N*) and add the rinsings to the main bulk of the liquid.

Add ammonium hydroxide (14*N*) until the liquid is definitely alkaline and then add excess (3 ml). Allow to stand for 5 minutes and then filter through a Whatman No. 40 filter paper (9 cm). Wash the precipitate four times alternately with water and ammonium hydroxide (1·4*N*), or until the washings are no longer blue in colour. Reject filtrate and washings. Dissolve the precipitate in hydrochloric acid (20 ml, 6*N*) and wash the paper thoroughly with hot water. Collect the solution and washings in a 100-ml beaker and arrange that the total volume of liquid is not more than 60 ml. Evaporate to incipient dryness on a hot plate, avoiding excessive heating of the residue.

Add hydrochloric acid (0·3 ml, 12*N*) and water (3 to 5 ml) to the residue in the beaker; heat until the iron and lead salts are dissolved. Add hydroxylamine hydrochloride solution (10 ml, 5 per cent) and boil for three minutes to reduce the iron to the ferrous state. Cool and quantitatively transfer the liquid to a 50-ml graduated flask containing gelatin solution (5 ml, 0·02 per cent). Slowly add hydrochloric acid (5 ml, 12*N*), gently swirling the contents of the flask during the addition. Make up to the mark with water and mix well. Pour a small quantity of the solution into the polarograph cell and pass hydrogen or nitrogen for 5 minutes.

Using a drop time of approximately 2½ seconds, record the polarogram over the range −0·2 to −0·7 volts applied potential. Carry out a blank determination on the reagents and calibrate the polarograph with lead standards treated in the same manner as the sample.

Base-exchange

Although many acid extraction procedures have been examined, none has been found to have a universal application. The success of the extraction is often affected by the composition and nature of the oil. However, it has been found possible to obtain a separation between ionic lead and lead present as TEL by using a base-exchange procedure as follows. The oil is diluted with an ionizing solvent, such as butyl cellosolve or *iso*propyl alcohol (IPA)–benzene mixture, and then the solution is passed through a bed of previously activated Zeocarb 215 base-exchange resin. Under these conditions, the ionic lead is retained on the resin and

the TEL passes on unchanged. After washing the bed free from oil and solvent, the ionic lead is extracted with hydrochloric acid, and the solution is used for the determination of lead by the polarographic method just described. This method has been used for the determination of traces of certain other cations in oil.

Table V shows the recovery of lead from oil by base exchange.

TABLE V

Recovery of Lead by Base Exchange (Zeocarb 215)

Sample	Lead present, % wt	Lead found, % wt	Recovery, %
TEL in oil	0·183	0·011	6
TEL + lead naphthenate in oil *	0·097	0·042	43
	0·210	0·110	52
Lead naphthenate in oil	0·210	0·210	100
	0·210	0·215	102
	0·210	0·192	96

* Equal amounts of both forms of lead.

A small recovery of lead was obtained from an oil containing TEL only. This is obviously produced by decomposition of the TEL, but it is not known whether or not this decomposition takes place during the passage of the sample through the resin.

Method 5: *Lead by Base Exchange on Zeocarb* 215

Activate Zeocarb 215 base-exchange resin by percolating hydrochloric acid (150 ml, 6*N*) through the resin (100 g). Wash free from acid and air-dry. Lightly pack the activated resin in a glass tube so as to form a column of resin approximately 8 inches high by 1 inch diameter. Percolate IPA (50 ml) and IPA–benzene (50 ml, 1 : 1) through the column to complete the drying process. Leave the column flooded with IPA–benzene mixture.

Dissolve the sample of oil (10 to 20 g) in IPA–benzene mixture (70 ml) and percolate through the column over a period of 10 minutes. Rinse the beaker with small quantities of IPA–benzene and transfer washings to the column. Wash with further quantities of IPA–benzene until the percolate is colourless; then percolate IPA (50 ml) and water (50 ml) through the column. Reject percolate and washings.

Extract the column with hydrochloric acid (150 ml, 6*N*) by percolating acid through column. Wash with two portions (2 × 50 ml) of water. Collect solution and washings in a 400-ml beaker and evaporate to dryness. Cool, add perchloric acid (3 to 5 ml), and again evaporate to dryness to destroy *traces* of organic matter. Treat residue in beaker and determine lead as described in the previous method for lead in lubricating oil.

SLUDGES AND ENGINE DEPOSITS

Analytical methods dealt with up to this point have been concerned with the determination of lead present as a minor constituent in liquid samples. In addition, the analysis is frequently required of solid samples of a number of types in which lead is generally a major constituent. These materials include the oil-insoluble suspended solids produced in engine lubricants during the prolonged use of leaded gasoline, sludge deposits resulting from the settling-out of suspended solids, and combustion chamber deposits. With the exception of spark-plug deposits, which are

dealt with later, all these materials are analysed for lead by a similar procedure. The only essential difference between their treatment is in the sample preparation required to free them from oil.

Suspended solids are recovered quantitatively from used oils by centrifuging in a Sharples super-centrifuge and washing the collected solids with petroleum spirit until free from oil. Sludge deposits are freed from oil by continuous extraction with hot petroleum spirit. Combustion chamber deposits are usually free from oil but, if oil is present, washing with petroleum spirit removes it in a satisfactory manner. The use of solvents other than petroleum spirit is avoided because they may remove certain lead salts and other essential constituents of oil-insolubles and sludge solids.

The amount of the sample available for the determination of lead is very often too small for the application of classical macro methods, and a polarographic method similar to that used in the determination of lead in oils has been adopted. It was found to be simple and rapid, and is now used as a routine procedure, even when sufficient sample is available for a macro-gravimetric determination to be carried out. Although the accuracy of the method is limited by the instrumental error, the results obtained are sufficiently accurate to provide the research chemist or engineer with the information required.

The sample is digested with nitric and perchloric acids, which dissolve the inorganic constituents and destroy organic matter. Lead is then determined by a modified version of the method for determining lead in oils. As tin is usually absent, treatment with hydrobromic acid can generally be omitted, and as in most samples the copper and barium contents are fairly low, this allows the ferric hydroxide co-precipitation step to be omitted also. It is then possible to deal with larger weights of lead, and consequently to take larger amounts of the sample. It is always arranged that the amount of lead is such that its concentration in the final solution is not high enough to cause objectionable polarographic phenomena. Although the quantity of sample used is generally 30 to 50 mg, if necessary the analysis can be carried out on 1 or 2 mg.

Method 6 : *Determination of Lead in Sludges and Engine Deposits*

Grind the dry, oil-free sample to a fine powder, and if particles of metal are present remove them by sieving, by hand picking, magnetically, or by any other convenient means. Mix the sample thoroughly and analyse it as follows :

(*a*) If the sample is suspected of containing high percentages of copper and/or barium, weigh out an amount containing not more than 5 mg of lead. Introduce the sample into a 100-ml beaker, add perchloric acid (5 ml, 12*N*) and nitric acid (5 ml, 16*N*), cover the beaker and digest on a hot plate until all organic matter has been destroyed and the sample is in solution. Raise the cover and heat until copious fumes of perchloric acid are given off. Cool and continue the analysis as for the determination of lead in oils, commencing at the stage at which the lead is co-precipitated on ferric hydroxide.

(*b*) If the sample is known to contain only low percentages of copper and/or barium, weigh out into a 100-ml beaker an amount containing not more than 50 mg of lead. Decompose the sample with perchloric and nitric acids as in (*a*) and evaporate the liquid to incipient dryness. Dissolve the residue in dilute hydrochloric acid, reduce iron with hydroxylamine hydrochloride, and continue the determination of lead as in the procedure for determining lead in oils. If more than 10 mg of lead are present use double quantities of hydrochloric acid, hydroxylamine hydrochloride, and gelatin solution and make up the final solution to a bulk of 100 ml instead of 50 ml.

In both procedures (*a*) and (*b*) use appropriate polarograph sensitivities to give polarographic waves as large as possible without loss of legibility in the polarograms.

Spark-plug Deposits

It is frequently of interest to know the percentages of metallic and combined lead in any deposit found on a spark plug. The total amount of deposit is usually small, seldom amounting to more than 20 mg, being more commonly of the order of 10 mg; it comprises mainly lead halides, lead oxide, lead sulphate, and varying amounts of metallic lead (generally less than 10 per cent).

A method which was found satisfactory for the determination of metallic and combined lead depends on their separation by treatment of the sample with sodium hydroxide solution. The lead compounds present in spark-plug deposits are converted to soluble sodium plumbite, while the metallic lead remains insoluble and can be filtered off by means of a filter stick. The metallic lead is dissolved from the stick with dilute nitric acid and, after evaporating to dryness, the residue is taken up in dilute hydrochloric acid and lead is determined polarographically. The combined lead, contained in the sodium hydroxide solution, can be determined directly on the polarograph, the sodium hydroxide in this case providing the supporting electrolyte.

No deposit samples of known metallic lead content were available for testing the method, but the procedure has been checked using mixtures of known composition, made up to correspond roughly with actual spark-plug deposits. The results obtained showed that the method can provide the information required. Errors found in the analysis of the synthetic samples are believed to be to some extent connected with difficulties in making up the mixtures and in sampling.

Method 7 : *Determination of Lead in Spark-plug Deposits*

Weigh out the sample on a thin glass slip (with an accuracy of 0·01 mg) and transfer the sample and the glass slip to a 100-ml beaker. Add sodium hydroxide solution (20 ml, 7 per cent), cover the beaker, and boil for 10 minutes, adding water as necessary to keep up the volume. Filter the liquid through a filter stick and wash the beaker and filter stick with water (six 5-ml portions).

Table VI

Spark-plug Deposits : the Analysis of Made-up Samples

Material	Wt taken, mg	Combined lead		Metallic lead	
		Present, %	Found, %	Present, %	Found, %
Lead + lead oxybromide	10·36	76·5	74·8	6·1	5·9
	9·83	76·5	75·2	6·1	5·6
	9·39	76·5	75·0	6·1	6·4
	11·35	76·5	74·5	6·1	5·6
Lead + lead oxybromide + 10% carbon added	9·15	76·5	77·1	6·1	6·1
	17·02	73·0	75·0	10·7	9·7
	16·40	80·3	78·0	2·0	2·4
Lead oxybromide	11·03	82·0	81·0	None	Trace

(i) *Metallic lead*

Dissolve the residue on the filter stick and in the beaker with nitric acid (5 ml, 5*N*) and evaporate the liquid to dryness. Add hydrochloric acid (0·3 ml, 12*N*) and water (10 ml), and bring to the boil. Add hydroxylamine hydrochloride solution to the boiling liquid to reduce any iron present, and from this point continue the determination as for the determination of lead in oils.

(ii) *Combined lead*

Make up the sodium hydroxide extract to a bulk of 100 ml. Pipette a 20-ml portion of the bulk solution into a 50-ml graduated flask, add gelatin (5 ml, 0·02 per cent) and dilute to the mark with water. Determine lead polarographically on this solution, recording a polarogram covering the range of potential −0·3 to −1·1 volts. The half-wave potential of lead in this case is at about −0·7 volts.

Acknowledgment

The authors wish to thank the directors of The Shell Petroleum Co. Ltd., for permission to publish this work.

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OBITUARY

EDWIN M. BAILEY

THROUGH the death on the 28 May 1953 of E. M. Bailey, in his eighty-seventh year, the Institute and the industry lost one of its oldest members.

He was probably the last remaining member of the team which, under the leadership of the late W. Fraser (father of the present Sir William Fraser), built up the prosperity of the Pumpherston Oil Company, subsequently playing an important part in the affairs of Scottish Oils Ltd.

Trained in the Department of Technical Chemistry endowed by Dr James Young of Kelly, in what is now the Royal Technical College, Glasgow, Mr Bailey entered the service of the Pumpherston Company in 1886, about eighteen months after actual operations had commenced. Eight years later he was appointed chief chemist, and he continued in that capacity for the long period of forty-two years until his retiral in 1936. In contrast with present-day conditions, which permit the shale industry to concentrate attention on a small group of products, for the greater part of Mr Bailey's career it was necessary to manufacture a multitude of grades of spirit, oils, and wax, in addition to sulphate of ammonia. His period of service in the industry covered practically the entire history of the internal combustion engine—first the oil engine using kerosine, then the petrol engine, and finally the compression-ignition type.

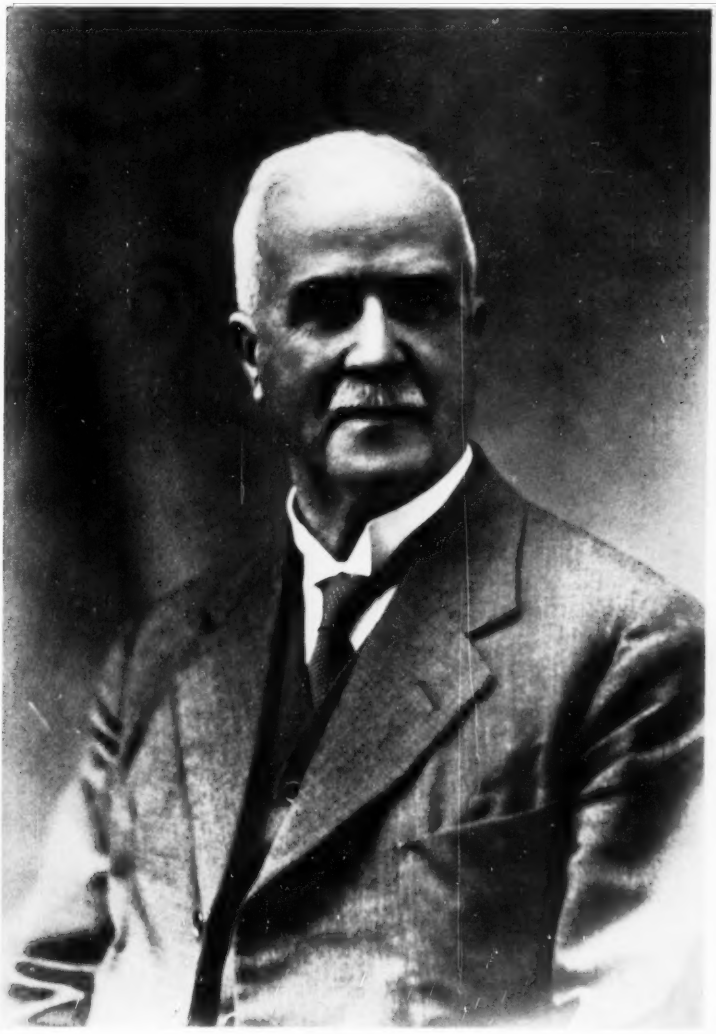
With the formation of Scottish Oils Ltd after world war I, combining the interests of all the shale companies then in existence in Scotland, Mr Bailey's sphere was greatly enlarged, and soon in 1924 was added the refining of Middle East crude petroleum at the new refinery at Grangemouth.

Previous to this Mr Bailey had carried out the experimental refining of petroleum from many different fields, including early samples from the Dutch East Indies and the first production from the prolific Spindletop field of Texas. Oil shales from every part of the world also passed through his hands, such work frequently including full scale retorting, followed by experimental refining of the crude oil.

His papers on the technology of the shale industry are to be found in the *Memoirs of the Scottish Geological Survey*, the *Journal* of the Institute, and records of the Empire Mining and Metallurgical Congress, and the Diesel Engine Users' Association, amongst other publications.

During his years of retirement he still continued to show a keen interest in scientific matters, and he spent much time on researches into the life, work, and personality of Dr James Young, pioneer and founder of the Scottish shale oil industry. A paper on the above subject was presented by him to the Scottish Branch of the Institute in 1948, and it was later published in the *IP Review* at the time of the centenary of the founding of the Scottish shale oil industry.

He was a man loved and respected by all his colleagues, especially his own staff. As a consequence of his deep interest in the industry, he was



EDWIN M. BAILEY

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always very willing to discuss the history and problems of shale oil with anyone who was anxious to glean knowledge and information from a master mind. His long devoted service, and excellent memory, caused him to be an outstanding figure, known throughout the shale oil world, but despite that, he retained his modest, reticent, and retiring disposition throughout the years of a long and active life. He had a keen sense of humour which, from the experience of those who served with him, helped to lighten the labours entailed in solving some of these awkward problems which arise in oil refining.

J. P. YOUNG

THE INSTITUTE OF PETROLEUM

An Ordinary General Meeting of the Institute was held at the Institution of Mechanical Engineers, Storey's Gate, London, S.W.1, on 22 April 1953, Dr E. B. Evans, vice-president, in the Chair.

The Minutes of the last Ordinary General Meeting, held on 8 April 1953, were read by the Editor, confirmed, and signed.

The chairman then introduced Mr C. B. Dicksee, who took the chair during the presentation and discussion of the following papers :—

SYMPOSIUM ON ENGINE TESTING OF LUBRICATING OILS

SOME ASPECTS INVOLVED IN THE EVALUATION OF ENGINE LUBRICATING OILS

Introduction

The difficulties of properly appraising an engine lubricating oil have gained a rapidly growing recognition over the past few years. Increasing knowledge of the shortcomings for such purposes of purely chemical tests in glassware has focused attention on engine tests. Many such tests have been proposed, and indeed included, in various specifications, but field experience with oils which have given promising results in laboratory engines has frequently been disappointing.

It is believed that these disappointments have been due to an inadequate consideration of the fundamentals of the evaluation of engine lubricating oils, and an attempt has been made in the present paper to reconsider very briefly the philosophy and practice of lubricating-oil testing. For convenience the paper consists of several short contributions, each concerned with a different aspect of the subject.

In Section I, which touches on the philosophy or basis of the evaluation of lubricating oils, an analogy is drawn between lubricating oil and other materials involved in engine construction. Just as the suitability of steel is judged by its ability to meet maximum requirements in terms of pertinent specific properties, so, it is contended, should lubricants be judged.

It follows that laboratory tests must be available for evaluating each of the pertinent specific properties of lubricants and that the maximum field requirements in terms of each of these properties must be determined. In Section II of the paper some examples of the types of laboratory engine tests involved are described, while Section III considers some aspects of the field-testing of oils through which field requirements are assessed.

In establishing laboratory engine tests involving the formation and assessment of engine deposits, care must be taken to ensure that the mechanism of their formation is substantially that obtaining in the field. The usefulness of chemical laboratory studies in this connexion is discussed in Sections IV and V.

Perhaps one of the most difficult of oil properties to measure accurately is its ability to reduce engine wear. It has been considered not out of place to include a short account (Section VI) of experiences using radioactive-tracer techniques for the assessment of wear.

As in most work of an experimental nature, in attempting to compare oils there can be frequent uncertainty regarding the significance of small performance differences. Such difficulties are met in both laboratory engine and field testing. Accordingly, where possible, statistical methods should be used in the planning of tests and analysis of results, and notes on this aspect appear in Section VII.

In a paper of this length it has been possible only to deal superficially with the various aspects of oil testing considered. It is hoped, however, that sufficient of interest is contained to stimulate thought and discussion and in such a way to contribute to the success of this symposium.

SECTION I. BASIC PRINCIPLES OF THE EVALUATION OF ENGINE LUBRICATING OILS

By Norman Kendall * (Associate Member) and L. J. Richards *

This section of the paper sets forth briefly some of the basic principles underlying the science of the testing and evaluation of engine lubricating oils. The following sections give an idea of the test methods and techniques used in exemplification of these principles.

In attempting to develop the principles underlying the evaluation of an engine lubricating oil, probably the most important concept which must first be accepted is that the oil is an integral material of construction of the engine, and for all purposes must be treated as such. As in the case of any materials of construction, the evaluation of the lubricating oil cannot be considered independently of the conditions under which it has to perform its duties; that is, it must be considered in relation to all factors such as engine design and engine operating conditions.

It may be simpler for the moment to consider an exact analogy—for instance, the selection of a steel for a critical engine component. In such a case, the specific properties required of the material may be defined by calculation, experiment, or experience; in one particular case, for instance, tensile strength, hardness, fatigue strength, and impact strength might be considered the only important pertinent characteristics. A steel of such a nature would then be selected so that each and every pertinent and specific characteristic was at least equal to the respective requirements. The devising of some overall assessment or means of evaluating the suitability of the steel would not be suggested. Similarly, a deficiency in respect of one particular property could not be compensated by superfluity in respect of any other.

The same principle is involved in the evaluation of a lubricating oil—a principle which, for want of a more suitable term, has been referred to as " specific evaluation." On such a principle the concept of a " performance

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pattern " can be useful. In Fig 1 the specific properties concerned in any particular case may be arranged along the base of the diagram (A, B, C . . .)

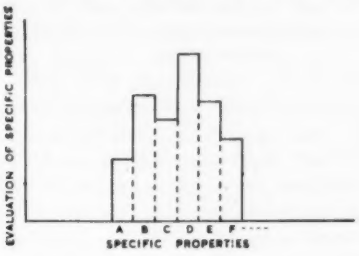

FIG 1

PERFORMANCE PATTERN OF AN ENGINE LUBRICATING OIL

and the respective values of each plotted on some arbitrary scale as ordinates. There are then two separate performance patterns of this nature :—

(*a*) that representing the requirements of any particular application (*i.e.*, taking into account the combination of engine-design/operating-conditions);

(*b*) that actually given by the oil being evaluated in order to determine suitability for this particular application.

To be satisfactory, the performance pattern (*b*) must satisfy completely, that is, it must fall outside, or above, the performance pattern (*a*) representing the requirements.

Bearing in mind these concepts, a logical approach to the subject of the evaluation of engine lubricating oils can be developed.

First, the requirements in respect of lubricating-oil characteristics for the particular application in mind must be established. In other words, the required performance pattern (*a*) must be established, and for this it is necessary to have recourse to the field and adequate facilities to observe closely the requirements in respect of the lubricating oil for any given range of application. This is actually one of the functions of " uncontrolled field tests."

The next stage is then to evaluate the proposed lubricating oil with respect to each of the pertinent specific properties and thence, by comparing this observed performance pattern with the required performance pattern, to make an assessment of the suitability of the oil for the particular application.

Such an assessment makes two basic demands :—

(i) field experience on which to define the required performance pattern;

(ii) ability to devise suitable methods for evaluating each specific property concerned.

Simple though these two demands may appear, in practice they present frustratingly complex difficulties. The first difficulty is in identifying and

characterizing many of the specific properties involved and in defining the operating conditions which are significant in any particular application. In fact, such difficulties are often virtually insuperable, and for this reason it is often necessary to resort to test engines rather than to glassware apparatus. The latter is always preferable on the score of cheapness, simplicity, and repeatability, but it does necessitate, first, a knowledge of the fundamental phenomena being observed and knowledge of all factors which may influence results. In the absence of such knowledge, the engine allows many of the complex factors encountered in practice (such as combustion, catalysis, mechanical effects, etc.) to be introduced, and if the end effects are similar to those encountered in practice (nature of lacquer, deposits, used oil, etc.) there is some measure of confidence that the significant operating factors have been introduced. The test engine must be regarded, however, as a piece of test apparatus, serving the dual role of being the means of introducing various pertinent factors, as well as a means of measuring the end effect on the oil and providing a negotiable entity by means of which performance can be expressed; the test engine should not be regarded as a scaled-down version of the engine used in the field or as a means of simulating conditions in the field.

SECTION II. SOME STANDARD TEST METHODS USED IN THE EVALUATION OF ENGINE LUBRICATING OILS

By J. ATKINSON * (Associate Fellow) and D. GOLOTHAN *

INTRODUCTION

THE test procedures briefly described here and which are used at Thornton Research Centre have been devised to assess some specific properties of lubricating oils. The properties that have been selected are ring-sticking, piston cleanliness, oil-ring blocking, and corrosion by seawater. Others which might also be included but which are not dealt with here are bearing-corrosion, wear, sludging, piston-ring groove packing, cylinder-bore lacquering, etc.

After having decided which properties it was required to evaluate, the procedures were ultimately arrived at by studying the effects of imposing different operating conditions on the engines. By so doing it was then possible to determine whether any one engine was more sensitive than another in respect of a particular factor, or whether it could be made so by modification. This approach is considered desirable if there are a number of engines available, since it should then be possible to make the best use of each. Provided that the desired effect can be achieved, however, it does not matter in what engine unit it is accomplished. Similarly, any suitable fuel may be selected that will contribute to the desired effect. It may be possible to measure two properties in a single test procedure, in which case the best use will be made of the additional data provided.

Notwithstanding the eventual success of efforts to produce good quality oils by utilizing specific evaluation tests, and in spite of the fact that in

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developing engine oils field tests are always arranged, cases may arise which, because of their association with a particular make and design of engine or the special conditions that are imposed on it in the field, make it essential to seek a solution by means of controlled field tests in that engine.

Fowler Engine Ring-sticking Test

This test evaluates H.D. oils with respect to sticking of the piston rings when temperatures in the ring zone are high. The engine is run under constant conditions of moderately high speed and load until ring-sticking occurs. The test is then terminated, and the running time taken as the criterion of the performance of the oil.

The performance of the oil is assessed by comparison with that of a straight mineral low-reference oil and an additive-type high-reference oil of MIL-0-2104 standard. The low-reference oil normally gives a ring-sticking time of 2 hours, and the high-reference oil 11 hours. The performance of the reference oils serve not only as a criterion for the ring-sticking times of other oils, but also as a check on the repeatability of results. In this test ring-sticking can still be obtained with high-ash oils, and a duration of 70 hours has in fact been obtained before ring-sticking occurred.

To accelerate ring-sticking, the standard piston is modified by machining an additional ring groove in the top land, thus bringing the top compression ring nearer to the combustion zone. Only one other compression ring is used, namely in the original top groove of the piston, Ring-sticking is indicated by an increase in blow-by as shown by a Drayton recorder and a manometer.

Operating conditions are :—

Engine	Fowler F.S.8 single-cylinder, compression-ignition engine specially designed for research work
Duration of test	Continuous running until ring-sticking occurs
Speed	1500 r.p.m.
B.m.e.p.	100 p.s.i. approx
B.h.p.	24
Fuel	Gas oil containing 1·0%w sulphur
Fuel consumption	10 lb/hour
Jacket coolant temp :	
Inlet	80° C
Outlet	85° C
Approx mean temp of top ring groove	270° C
Oil inlet temp	75° C
Oil in system	2 I.G.
Oil pressure	20 p.s.i.

Gardner Engine Piston-cleanliness Test

In this test the criterion of oil performance is the quantity of lacquer and carbon deposits formed on the piston skirt under medium-speed, medium-output conditions. At the end of test the piston is given a cleanliness merit rating, based on the quantity and nature of deposit. A straight mineral oil gives a rating of about 4·0, while an oil of MIL-0-2104 standard rates at about 9·0. The test is not, therefore, severe enough for rating oils above this standard.

Operating conditions are :—

Engine	Gardner L.2 type, single-cylinder compression-ignition engine
Duration of test	25 hours (continuous running)
Speed	1000 r.p.m.
B.m.e.p.	90 p.s.i. approx
B.h.p.	10
Fuel	Gas oil containing 1·0%w sulphur
Fuel consumption	3·75 pints/hour
Jacket coolant temp :	
Inlet	80° C
Outlet	82° C
Sump oil temp	65° C approx (uncontrolled)
Oil in system	6·9 pints
Make-up oil added	None
Oil pressure	20 p.s.i.

Crossley Engine Ring-blocking Test

This test evaluates lubricating oil performance with respect to blocking of the piston scraper rings by carbon deposits. The engine is run under cycling conditions simulating automotive operation, and the test duration is made reasonably short by using a low-cetane high-sulphur distillate fuel which has been found to be especially prone to form deposit in the rings. With a straight mineral oil, blocking is of the order of 60 per cent in the top scraper ring and 30 per cent in the bottom scraper; additive oils give markedly less blocking than this.

Operating conditions are :—

Engine	Crossley BVD1 single-cylinder compression-ignition engine
Duration of test	20 cycles of 4½ hours each (total of 90 hours), the conditions for each cycle being :

Phase	Condition	Speed, r.p.m.	Load, kW	Duration, min
1	Idling	1500	—	15
2	Light load	1500	2	15
3	Full load	1500	5·3	105
4	Overload	1500	6	15
5	Light load	1500	2	120

Test fuel	High-sulphur (2·8%w) distillate gas oil
Oil in sump	4 pints
Oil make-up	Continuous
Sump oil temp	80° C approx (uncontrolled)
Cylinder jacket temp	80° C

National Engine Seawater Corrosion Test

This evaluates the ability of the lubricating oil to resist corrosion and sludging when seawater is added to the oil, a problem likely to be encountered in marine practice, where seawater is used for cooling the cylinder jackets. The coolant may find its way into the oil storage tanks or engine crankcase, in which case it will be circulated with the oil and may cause severe corrosion of piston rings and skirts, cylinder liners, and other components, and in addition may be responsible for the precipitation of heavy sludge and salt deposits.

In the National engine test the engine is run continuously for 30 hours at medium speed and load, with synthetic seawater added to the lubricating oil at a constant rate throughout the test. The principal criteria of oil performance are corrosion of the piston and other engine components and the extent of sludging in the crankcase and external oil tank. With a straight mineral oil, corrosion is severe and fairly considerable quantities of engine sludge are formed. There are marked differences between various additive oils in effecting improvements in these respects.

Operating conditions are :—

Engine	National DAPI single-cylinder compression-ignition engine
Duration of test	30 hours
Speed	1000 r.p.m.
B.m.e.p.	70 p.s.i.
Cylinder jacket temp, outlet	50° C
Oil tank temperature	50° C approx (uncontrolled)
Rate of addition of synthetic seawater to lub oil system	150 ml/hour
Total oil charge	16 pints
Oil make-up	None
Fuel	Gas oil containing 1·0%w sulphur

Petter Engine LA.3 Piston Cleanliness Test

This test evaluates the performance of H.D. oils with respect to their tendency to form piston lacquer and carbon deposits at high operating temperatures, under which conditions the fuel plays little part in such formation. The principal criteria of oil performance are the deposits on the piston skirt and undercrown, but deposits in the scraper ring are also taken into account. The piston is inspected and rated at intermediate periods during test, as well as at the end of test, so that the rate of formation of deposits may be studied.

The test is considered to be too severe for the evaluation of straight mineral oils, which give a very dirty piston. The procedure is used mainly for oils of MIL-0-2104 standard; with oils of higher performance the piston skirt and undercrown are generally clean.

Operating conditions are :—

Engine	Petter Series II single-cylinder gasoline engine
Duration	48 hours
Speed	1540 r.p.m.
B.m.e.p.	65 p.s.i. approx
B.h.p.	3·6
Induction air temp	50° C
Fuel	73 octane straight-run unleaded gasoline
Specific fuel consumption	0·75 pints/b.h.p.hr
Jacket coolant temp	160° C
Sump oil temperature	130° C
Oil in system	3 pints
Make-up added	None

The piston is inspected and rated at 16 and 32 hours, as well as at the end of test.

SECTION III. FIELD TESTING AND THE EVALUATION OF DIESEL LUBRICATING OILS

By S. C. Whitehead * and W. A. Snell * (Associate Fellow)

Purpose of Field Testing

As already pointed out in Section I, field tests of lubricating oils are carried out for two reasons :—

(1) to obtain information on performance of existing grades in order to investigate whether laboratory engine tests are giving good correlation with the field;

(2) to test under actual service conditions experimental oils which have previously been engine-tested in the laboratory.

It might be thought that ample information about the performance of existing grades would already be available to oil marketers, but this is not so. The available information is often incomplete in some respects; for instance, definite cylinder-bore wear figures may not be available for well-defined conditions of operation. Field tests are also of great value to those on the research side as one of the means of maintaining contact with the field.

The other main purpose of testing existing grades is to establish a standard of performance against which the performance of experimental oils can be judged. This standard of performance must be viewed from the users' angle, *i.e.*, emphasis must be placed on criteria of importance to the user, rather than on criteria which are convenient when evaluating oils in the laboratory. The two are not necessarily identical; for example, piston cleanliness ratings are the criterion in some laboratory engine tests, but these may be of little interest in the field. Ring-sticking, oil-ring plugging, or cylinder-bore wear are of paramount importance in service, and are factors which may impose limitations on engine overhaul periods; they should therefore be kept well to the fore when assessing field results.

The most important purpose of field trials is to evaluate experimental oils under actual service conditions. Such oils, although called here "experimental," are, in fact, oils which have been thoroughly engine-tested in the laboratory, field testing being the final stage in the evaluation of a new oil.

A third reason why road trials are sometimes carried out is when some specific complaint arises in the field, and it may be uncertain whether the cause of the trouble is of a mechanical nature or can be attributed to the poor performance of the oil. In many cases a bench test may be a suitable means of investigation but in others road trials are more appropriate.

Controlled and Uncontrolled Field Tests

Field trials may be divided into two categories, controlled and uncontrolled. Controlled tests are those in which the vehicles are run on a fixed schedule and are not used for their normal purpose of passenger or goods

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carrying. The expense of such a test is very heavy, probably as much per vehicle used as a bench test of similar duration. It is, therefore, usually necessary to confine such a test to a comparatively short duration, and to motor cars, as the expense of acquiring and running large commercial vehicles would be prohibitive. Also, since such vehicles as the latter are frequently used on regular runs in normal service, it is usually possible to find suitable fleets of vehicles in which to run uncontrolled tests.

General Procedure for Uncontrolled Tests

It will be of interest to describe the general procedure adopted at Thornton in running uncontrolled field tests. The first problem, and one of the most difficult, is to locate a suitable fleet of vehicles, working under the particular operating conditions which are of interest. The fleet should be of sufficient size, should be well controlled and used as far as possible on regular runs, and managed by persons who are prepared to take an interest in the tests and ensure that the correct oil is used and that regular oil changes are carried out. Additionally, in order to limit the tests to a practical duration, it is important to choose a fleet whose vehicles run big mileages per year.

The number of vehicles to be used will depend on various factors, including the number of oils to be tested, the availability of vehicles of the same make and type, and the number of different routes and loads on which the vehicles are used. Experience at Thornton leads to the belief that a minimum of five vehicles on each oil, all of the same make and type and all used on a similar type of service and load, will enable reliable conclusions to be drawn. By exercising careful control over the test vehicles it has been found possible to obtain reliable results from each vehicle. When the number of vehicles involved becomes very large, the history of each vehicle during test is more difficult to determine. Nevertheless, if a greater number of vehicles is available they should be used, and operators of large homogeneous fleets, such as bus fleets, are in a very fortunate position in this respect.

It should be also borne in mind that in tests of this nature what is being sought is differences in performance between oils that will be significant in practice—differences, that is, sufficiently large to be readily appreciated in field service.

Practical Details in Uncontrolled Tests

From the practical aspect it is necessary to start the test with a new or newly overhauled engine in each vehicle. This should include re-bored or re-sleeved cylinder blocks, new pistons and rings, new or reground crankshaft, and new bearing shells. Before assembly of the engine, measurements are taken, including piston ring weights, gaps and side clearances, cylinder-bore dimensions and, if bearing wear is to be measured, bearing shell weights and crankpin dimensions. The engine is then assembled and run-in according to normal procedure, and put into service using the test oil.

The test vehicles are then used in normal service for the full overhaul period of the engine. The length of this period varies widely between

different operators, anything from 50,000 to 200,000 miles between major overhauls being common practice for diesel engines.

It is essential that oil changes should be carried out at regular intervals, and a sample of the used oil taken at each change and sent for analysis. Samples should be analysed immediately, as they indicate whether the engine is operating satisfactorily and also whether the correct oil is actually being used, the latter being a factor which is not always as easy to ensure as it might seem.

When the engine is due for overhaul it is completely stripped for inspection. Particular regard is taken of ring-sticking, scraper-ring blockage, general crankcase sludging, oil-pump intake screen deposits, and bearing and valve condition. Cylinder bores are measured for wear, and piston rings weighed and measured as before the test. This work is carried out on all the test vehicles, and the results on the different oils compared.

Typical Results from Uncontrolled Tests

Some of the results that have been obtained in uncontrolled road tests run according to the above procedure are now considered. In one such test a fleet of fifteen long-distance goods haulage vehicles, all fitted with the same make of engine and operated on similar routes and loads, were used. Four oils were tested :—

> Oils A and B were straight mineral oils,
>
> Oils C and D were detergent additive oils, formulated from Oil A but containing different types of additive, the additive contents being similar in terms of ash.

The original intention was to run on three oils only; thus fifteen vehicles were required, but during the course of the tests it was decided that another straight mineral oil (Oil B) should be tested. As further vehicles were not available for test it was necessary to use vehicles in which it had been intended to test Oil A. For the purpose of calculating percentage reduction in wear obtained by using the additive oils, the results on the two straight mineral oils (A and B) have been taken together.

In these particular tests the opportunity was taken of investigating the effect on wear of fitting a chrome-plated top piston ring. In six of the engines each alternate piston was fitted with a chrome-plated top ring, thus enabling a direct comparison of wear to be obtained.

The results are given in Table I.

The following conclusions were drawn from the results :—

1. Oil A was unsuitable for use in this type of service, as it gave early onset of ring-sticking and heavy carbon deposits on the pistons.
2. Oil B gave satisfactory service up to 100,000 miles, but considerable cold ring-sticking was found at the end of test. Complete blockage of oil scraper-rings and heavy sludge deposits in the crankcase occurred.
3. Oil C gave a considerable improvement over oils A and B with respect to ring-sticking and general engine cleanliness, and a significant reduction in ring wear, but reduction in bore wear was erratic (nil to 50 per cent).

TABLE I

Road Tests in Diesel-engined Vehicles

Vehicle No.	C/18	C/41	C/48	C/48	C/55	C/52	C/38	C/43
Oil	A	A	A	B	B	B	C	C
Mileage	46,000	57,000	33,000	60,000	97,000	86,750	89,000	92,400
Ring-sticking rating	8·2	—	4·5	9·3	8·1	—	10	8
Scraper ring clogging, %	100	100	83	98	89	—	18	19
Top groove carbon, g	0·77	—	0·82	0·75	0·91	—	0·93	0·85
Bore wear, 10^{-3} inch per 10,000 miles	H 1·1	—	—	H 1·15	Cr 1·20 / H 1·40	Cr 1·62	H 0·66	H 1·14
Ring wear, g per 10,000 miles	1·21	H 1·20	Cr 1·12 / H 1·40	1·10	1·05 / 1·30	—	0·83	1·17

Vehicle No.	C/54	C/50	C/56	C/40	C/49	C/51	C/53	C/42
Oil	C	C	C	D	D	D	D	D
Mileage	91,900	92,300	108,000	74,400	132,900	115,000	115,000	107,000
Ring-sticking rating	7·2	9·2	7·5	10	10	10	10	10
Scraper ring clogging, %	100	79	87	8	47	86	67	8
Top groove carbon, g	0·79	0·84	0·87	0·42	0·54	0·34	0·43	0·39
Bore wear, 10^{-3} inch per 10,000 miles	Cr 0·55 / H 1·35	Cr 0·79 / H 1·62	Cr 0·66	H 0·50	Cr 0·45 / H 0·74	Cr 0·50 / H 0·87	Cr 0·53	H 0·64
Ring wear, g per 10,000 miles	0·43	0·77	0·59	0·97	0·63	0·55	0·49	0·62	0·48	0·81	0·52	0·65

H = Hardened top piston ring.
Cr = Chrome-plated top piston ring.
The oil change period on all vehicles was 5000 miles.

4. The use of Oil D effected a further marked improvement in engine cleanliness and completely eliminated ring-sticking, while scraper-ring clogging was greatly reduced. There was a consistent reduction in ring and bore wear amounting to averages of 47 and 43 per cent respectively compared to the non-additive oils A and B when using hardened top piston rings, and 54 and 65 per cent respectively when using chrome-plated top piston rings.

5. The use of chromium-plated top piston rings effected considerable reduction in both ring and bore wear with all the oils, but with the non-additive oils this reduction was largely dependent on the total distance run, as the chromium wears off after about 50,000 miles, and wear rates then revert to normal. With the additive oils, there was still some chromium remaining after 90,000 to 100,000 miles.

The results obtained in these tests were of very considerable value, enabling an assessment to be made of the significance of laboratory bench-test on the same oils. The results were of special value in providing data on cylinder-bore and ring wear, since there is usually some uncertainty how far wear data obtained in laboratory tests will represent results in service.

Tests are also being run in fleets used on other types of service, such as city bus operation, and medium-distance fuel delivery work, the latter service including use of engines for pumping duty. The results of all these tests will permit a better assessment of the oil requirements for each type of service on a sound basis, and the determination of which combination of base oil and additive is most suitable in each case. The results will also provide valuable data to compare with results obtained in laboratory engine tests.

Advantages and Disadvantages of Uncontrolled Tests

The major disadvantage of uncontrolled road tests is the length of time required to complete the work. A period of two years from the start of the tests can be regarded as the minimum time taken if the full overhaul life of the engine is to be used. Using the latest additive oils, overhaul periods of 200,000 miles have become possible with the diesel engine, which means four years' running, but in some types of service overhaul periods are considerably shorter and give more ready scope for improvement by the use of better oils.

It is considered to be essential to run uncontrolled tests for the full overhaul life of the engine, as results obtained over shorter periods can be misleading. Wear rates tend to decrease with total mileage, and in comparing wear figures care must be taken that they are taken over comparable mileages.

The chief advantages of uncontrolled road tests compared with other methods of test (*i.e.*, laboratory engine tests or controlled road tests) are that the oil is tested under actual service conditions, and the cost in terms of both money and man-hours is relatively small.

SECTION IV. THE DIAGNOSIS OF ENGINE DEPOSIT PROBLEMS

By J. HUGHES * and C. R. MAJOR *

INTRODUCTION

THE ability of oils to maintain clean engines and prevent the formation of deposits is assessed by evaluating specific properties such as piston cleanliness, oil-ring blocking, and ring-sticking. Many factors besides the lubricating oil affect this aspect of performance, *e.g.*, engine design, operating conditions, and fuel, and these are taken into account, but, in service, combinations of these factors sometimes occur that give rise to deposit problems. Whatever the underlying cause of the problem, the resulting trouble can often be alleviated by changes in the lubricant, and it is the aspect of the problem which concerns the lubricating oil that is dealt with here.

The problems arising in service as a result of the formation of engine deposits are numerous and varied. The formation of the deposit may be confined to a particular make or type of engine and associated with some unsatisfactory engine design feature; on the other hand, the deposit may have been formed in an engine of known satisfactory design, but under conditions of operating severity far in excess of normal practice. Problems of this nature, or "localized problems" as they might be termed, can usually be characterized as such by analysis of the particular deposit and the intepretation of these data in the light of a general background of experience of the performance of various engine types in service. However, there remain the problems which occur in one or more types of engine of satisfactory design run under typical service conditions, and in which it is apparent that the lubricating oil is inadequate to meet the demands imposed upon it. It is this latter type, or "general problem," that is of importance in the development of H.D. oils.

Broadly speaking, the problems encountered concern the formation of deposits which interfere with the normal operation of the engine, and the ultimate aim is to maintain development of oils abreast of advances in engine design and application. The development of lubricating oils invariably entails as a first step the study of the problems experienced in the field; following this, laboratory engine tests designed to produce similar phenomena are set up along the lines already discussed in Section I. The most usual method in the past has been to run an engine in the laboratory under conditions typical of what is regarded as average service, or even under purely arbitrary conditions, in an attempt to produce deposits having the same appearance as those in service. Having accomplished this, the next step was to try to cure the trouble by using various available additives. In some simple cases such a procedure may be quite satisfactory, but it may easily lead to considerable wasted effort and erroneous results. The deposit found in service and that formed in the laboratory, although appearing similar, may differ appreciably in their compositions and mechanisms of formation. The laboratory procedure is not of much use if it is assessing

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the formation of "chalk" whilst the deposit being laid down in service is more characteristic of "cheese." Furthermore, in such circumstances the fact that a particular additive alleviates the problem in the laboratory engine does not mean that the same additive will prevent deposition in the field. Even if it does, it does not follow that the problem has been attacked at its root or overcome in the best way.

The object of this section of the paper is to outline some steps which can be taken by a research centre to elucidate the field problem and subsequently to check that any test procedure set up does evaluate the true problem. In addition, this approach should be of assistance in the choice of additives for solving the problem on a scientific basis.

Reviewing the Problem

The review of any specific problem involving engine deposits should be carried out jointly by the engineer and the chemist, the former being concerned with the effect, extent, and general significance of the deposit, and the latter with the mechanism of its formation. Both of these tasks call for appreciable background experience.

During his investigation of the problem the engineer should consider :—

(*a*) The types of engines in which the problem is manifest and any particular design features common to these engine types.

(*b*) The operating conditions under which the problem occurs, including such factors as load, oil and coolant temperatures, type of fuel, periods of operation, etc. Furthermore, he should endeavour to obtain some idea of the temperatures of the engine parts on which the deposit has formed.

(*c*) Secondary effects resulting from the accumulation of deposits.

(*d*) Possible alleviation of the problem by changes in operating techniques or by mechanical modification, particularly if the problem is "localized."

(*e*) Any technical restrictions on the introduction of new lubricating oils into the particular service, *e.g.*, the possibility of Streamline filtration.

At the same time, samples of the undesirable deposit should be procured for investigation by the chemist. He will examine the deposit, together with any available used-oil samples, and possibly fuel samples, to obtain as clear a picture as possible of :—

(i) the composition of the deposit;
(ii) the origin of the deposit;
(iii) the probable mechanism of formation and deposition;
(iv) the lubricating-oil property likely to have the greatest influence in reducing deposition.

The chemical aspects of the problem, that is the mechanisms of formation of the deposit, its composition and origin, will be discussed first and consideration given to how such information may indicate in what specific property the oil used had proved deficient.

The Constitution of Engine Deposits

Many different types of material can be deposited in the oil system of an internal combustion engine. The different deposit types are usually called sludge, lacquer, carbon, etc., according to their appearance. These terms are unsatisfactory in that they give no indication of the origin or mechanism of formation of the deposit. The term " carbon " does imply that the constitution of the deposit is known, but in fact this is very misleading, as the so-called " carbons " formed in engines (for example, on piston undercrowns) sometimes contain as little as 5%w of elementary or free carbon and rarely contain more than 40%w.

A better understanding of these deposits is gained when it is realized that all of them are mixtures of constituents produced by any or all of the following mechanisms :—

(1) incomplete combustion of fuel;
(2) incomplete combustion of lubricant;
(3) oxidative polymerization of fuel;
(4) oxidative polymerization of lubricant.

Deposits formed from (1) and (2) are soots and have a high (*ca* 70%) free carbon content. Those from (3) and (4) represent a variety of products varying over a wide range of molecular weights, solubilities, and physical properties, *i.e.*, from sticky cylinder-bore lacquers to hard piston undercrown deposits. The transition from soft, readily soluble, to hard highly insoluble material is most probably a further polymerization, and usually results from prolonged baking of the deposit.

The above mechanisms account only for the production of the material which forms the deposit; the processes whereby it is deposited on the engine parts are more complicated and are briefly considered later.

Methods of Deposit Analysis

The details of the rather lengthy methods whereby engine deposits may be analysed are outside the scope of this paper. It is intended that these details will be published in the near future. However, a short account showing the scope of the present methods of deposit analysis is given below.

A technique has been developed which assesses the sum contribution to deposit formation made by combustion mechanisms (1) and (2). This assessment of combustion products, together with an inorganic analysis of the deposit, itself determines by difference the contribution to deposit formation of mechanisms (3) and (4). The products of these latter two mechanisms can generally be distinguished in cases where the fuel and lubricant differ fairly widely in properties, *e.g.*, molecular-weight range. This is usually the case in gasoline engines and in high-speed diesels (in which distillate gas oil is the usual fuel), but is not true in the case of diesel engines running on fuels containing residual components. Analytical methods are thus available which can separate the organic (or carbonaceous) portion of the deposit quantitatively into combustion products and oxidative polymers and which can assess in many cases whether fuel or lubricant was the prime contributor to this polymerized portion of the deposit. The inorganic portion of the deposit is much easier to tackle, and its various components

can usually be assessed quantitatively. Inorganic material does not usually make a large contribution to diesel-engine deposits, but the presence of even small quantities of metals can be very useful tracers in characterizing oil or fuel products in the deposit.

Laboratory Investigation of the Problem

Having described how the problem should be reviewed in the field, and considered the analytical steps needed to elucidate the origins of deposits, the interpretation of these data must be considered. The use of the results is most easily illustrated by a few hypothetical examples. Deposits of the constitution shown in these examples have actually been removed from engines in the field, so that the problems considered are realistic ones.

Example (1) : *Exhaust-port Deposition*

Two-stroke diesel engines are liable to heavy deposition in exhaust ports. These port deposits appear to be of two types, depending on whether or not the lubricant has played a major part in deposit formation. The two types, which are identical in appearance, are :—

(*a*) deposits consisting of about 70%w of soot, almost certainly from the fuel, the remaining 30%w being polymerization material also formed chiefly from the fuel;

(*b*) deposits containing less than 40%w of soot, the main precursor of the polymerized material being the lubricant.

It is probable that deposit (*b*) is actually a mixture of deposit (*a*) and large amounts of lubricant polymers.

If, in investigation of a field problem of exhaust-port blocking, the deposit is found to be of the first type (*i.e.*, formed almost entirely from the fuel), then the fundamental solution of the problem is to improve combustion efficiency. The lubricating oil property most likely to reduce deposition is obviously detergency, but it may be that insufficient oil reaches the exhaust port for detergent additives to have any pronounced effect.

The composition of deposits of the second type shows that appreciable quantities of oil reach the exhaust port, and in this case there would appear to be more scope for attacking the problem via the lubricating oil. A lubricating oil of extremely good oxidation stability may directly reduce the lubricant oxidation products which on polymerization give rise to the major portion of the deposit. If, however, the high temperatures prevailing in the exhaust port make this impracticable, an alternative solution would be to incorporate in the oil an additive which would prevent polymerization or deposition.

Example (2) : *Piston Deposits*

The piston deposits which are most likely to call for the use of an H.D. lubricant are those formed in piston ring grooves. These again are of two types :—

(*a*) Deposits consisting chiefly of combustion products (soot) bound together by small quantities of polymeric material.

(*b*) Deposits containing relatively little soot and consisting largely of polymers to which fuel and lubricant both contribute. Fuel usually plays the major part.

The formation of both types of deposit can be considerably reduced by using a detergent oil. Detergency, however, is a wide term covering a multitude of actions, and it is doubtful whether the mechanism by which soot particles are kept in suspension in the oil is the same detergency function as that by which fuel (or oil) polymers—which may easily be moderately soluble in oil—are prevented from depositing. A single engine test need not necessarily assess both of these detergency functions.

Example (3) : *Crankcase Deposits*

In crankcase deposits fuel polymers are uncommon and three types of deposit occur. These are :—

(*a*) those consisting chiefly of combustion products;
(*b*) polymeric material resulting from oil oxidation;
(*c*) cold sludge.

This last deposit, the frequently occurring mayonnaise-type sludge, is in the main an emulsion of water and oil, and is rarely met within the field of H.D. lubricants. It will not be considered further. Type (*a*) is similar to the type (*a*) ring-groove deposit discussed earlier, and requires the same remedy. In seeking to develop oils to overcome the deposition of lacquer-like material formed from oil oxidation and polymerization (type (*b*)) it is worth while considering the probable steps by which such a deposit gets into the engine. First, the oil is oxidized to primary oxidation products. These products then polymerize to form the deposit, which is then laid down on engine parts. (These last two steps are probably not separable, as the polymerization step may perhaps occur only in the proximity of metal.) If this hypothesis is correct, then deposition could be prevented either by improved anti-oxidant characteristics to interfere with the first step, by the incorporation of some additive which would inhibit polymerization, or by preventing the material, once formed, from depositing on engine parts. Consequently, the problem is similar to that of type (*b*) exhaust-port deposits. However, the solution to the problem should be considerably easier, because crankcase deposits are formed at much lower temperatures.

The formation of different types of crankcase deposits again may have to be assessed by different engine tests.

On completion of field and chemical investigations the research team is in a position to throw considerable light on the questions :—

(*a*) Is there a " general problem ? "
(*b*) If so, what exactly is the problem ?
(*c*) What are the pertinent factors associated with the problem ?
(*d*) What appears to be the approach most likely to solve the problem ?

It is thus in a position to proceed with the setting up of a laboratory engine test and an oil development programme along logical lines.

Development of the Test Procedure

The pertinent factors to be considered in the development of the test are:—

(*a*) type of engine to be used;
(*b*) modifications necessary to adapt it to the particular problem;
(*c*) operating conditions under which it should be run.

The information gained from the field regarding the types of engines in which the problem is manifest and the design features common to these engine types gives the best indication as to the most suitable type of engine to be adopted. To attempt to develop the test on an engine which is inherently insensitive to the particular problem necessitates its operation under conditions so unreal as to make the interpretation of results extremely difficult.

Having selected an engine which, on the basis of the information available, is considered suitable, steps should then be taken to bring pertinent conditions into line with those in service which gave rise to the particular problem. For example, such ratios as total cylinder-bore swept area to oil charge, oil consumption to oil charge, blow-by to oil charge, fuel consumption to oil consumption should be the same as those in service. This may necessitate suitable modifications to the installation.

Knowledge of the composition of the deposit under investigation will influence the decision as to the conditions under which the engine should be run. These conditions should not, however, be too far removed from those obtaining in the particular engine types in service. Careful consideration should be given to the fuel to be used for test purposes, particularly if the fuel is suspected or known to be a major contributor to the deposit formation.

Having conducted provisional tests, and obtained a deposit similar in appearance to that in service, the deposit should be analysed to ensure that it is in fact of the same type as that formed in service. If the time taken to produce the deposit is too long, modifications to the operating conditions should be made. Care should be taken, however, to ensure that these modifications do not alter the type of deposit produced. When this has been achieved satisfactorily, the programme of oil development work can then proceed along the lines suggested by the results of deposit analysis.

SECTION V. THE USEFULNESS OF OIL ANALYSIS IN THE EVALUATION OF ENGINE LUBRICATING OILS

By K. Fleming * and J. Hughes *

Introduction

Present-day trends in engine design and operating conditions and unavoidable changes in the types of fuel available for consumption all contribute to the increasing problems of engine operation. New oils (H.D.) are required to alleviate these problems in C.I. engines, but the development of

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these oils must be done in a rational way. An H.D. oil must be " tailored " to overcome the problems which have been encountered in C.I. engines in service. Much of this tailoring must inevitably be done in laboratory engine tests.

The approach to the development and application of such engine tests is the subject of Section I of this paper, and this section discusses the value of used-oil analysis both in the elucidation of the oil properties in service and in the developing and running of suitable laboratory tests. First, however, it is useful to review the type of information which can be obtained from used-oil analysis, *i.e.*, the nature of oil contaminants and also the methods used in gaining this information.

The Contamination of Lubricating Oils

According to their origin, the contaminants in a used oil can be divided into :—

(*a*) intrinsic contaminants, which arise from the reactions of the oil itself within the crankcase and oil system;

(*b*) extrinsic contaminants, formed by incomplete combustion of fuel, or by engine wear, or which enter the oil from the atmosphere with the intake air;

(*c*) contaminants which arise from the fuel–oil interactions.

These contaminants may be further divided into those which are oil-soluble and those which are oil-insoluble but remain in fairly stable suspension in the oil.

The intrinsic contaminants are governed directly by the quality of the lubricant, and depend also on engine design and operating conditions. Extrinsic contaminants are independent of lubricant quality, being governed by fuel quality and again engine design and operating conditions. Nevertheless, the oil must minimize any harmful effects which might arise from these extrinsic contaminants. H.D. oils were in fact first developed for this purpose.

Many papers on oil contamination [1,2,3] have been published. It is sufficient here to list the most common contaminants in the above groups. Intrinsic contaminants consist largely of products of the oxidation of the lubricant and of soluble and insoluble additive depletion products. Polymerization of these primary oxidation products may occur, and if the oxidation is severe this may lead to deposit formation. In general, however, oil oxidation products remain oil-soluble, and the direct formation of oil-insolubles by oil oxidation appears to occur only with LVI oils under high-temperature conditions.

Extrinsic contaminants from the combustion chamber include fuel soot, unburnt fuel, water, dust, etc.

Additionally, there may be present both soluble and insoluble products from piston rings, cylinder walls, bearings, etc.

The quantities of the various types of contaminants vary widely with engine conditions,[2] and the degree of contamination can be considered only in relative terms of normal and abnormal.

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Examination of Used Oils

Both chemical and physical methods which have been standardized by various authorities are used in the examination of used oils. These methods in general have limitations which are well recognized and often give approximate results only. The introduction of additive oils has rendered unsuitable certain of the older analytical techniques, and newer methods have been developed or will require development if results of any significance are to be obtained.

Essentially a used-oil analysis involves the quantitative separation of insolubles from the oil; the insolubles and clarified oil are then examined separately. The method used at Thornton Research Centre for determining and examining oil-insolubles has recently been described.[3] The oil-insolubles content is determined by filtration of the oil at 90° C through a bacteriological filter ("Sterimat") held in a special light-weight holder. The insolubles are then extracted from the pad by benzene or chloroform and the nature of the inorganic matter determined separately. The clarified oil is examined for soluble metal content either by chemical or by spectrographic method,[4] for total base number by electrometric titration, and in some cases for oil-soluble contaminants by adsorption upon a suitable earth (a modification of an ASTM proposed method). The viscosity, the fuel diluent, and total iron content are determined separately.

Acid values are not determined upon used additive type oils, because of the lack of significance [5] of the values obtained. Many additives, even those of an essentially basic nature and containing no free acids, will give acid values on titration with potassium hydroxide according to standard methods. This anomaly arises from the nature of the additive, particularly the metal which is present. Zinc, a weak base, is readily displaced by potassium hydroxide, a strong base, so that zinc additives will in general give acid values. Since additive depletion occurs in service, the contribution of the additive itself to the acid value will vary. Consequently it becomes impossible to attach any significance to the acid value found, even as a relative indication of oil deterioration.

The method of clarifying oils and estimating oil-insolubles by "Sterimat" filtration [3] was developed because, with the advent of additive oils, standard methods for the analysis of used crankcase oil became unsuitable. In the standard method a used oil is diluted with petroleum ether to cause flocculation of the oil-insolubles prior to their removal by filtration through a Whatman type filter. With H.D. oils, however, this flocculation after dilution is not always complete, and removal of insolubles will therefore be incomplete.

Soluble metal contents are determined as a guide to the concentrations present in the clarified oil of unchanged additives and also of soluble wear and corrosion products which may have catalytic properties and may therefore affect oil performance. These determinations are made either by spectrographic or chemical methods specific to the metal concerned. Sulphated-ash determinations on used additive oils are of limited value unless the ash composition is determined. In any case the optimum conditions for carrying out the ashing vary from metal to metal, *e.g.*, the temperature with zinc should not exceed 600° C, whereas calcium sulphate is stable at 800° C.

Irrespective of the method employed, the value of soluble metal determinations is limited in certain cases, *e.g.*, in an oil containing two additives with a common metal which deplete at different rates. The soluble metal content *per se* will not indicate the amount of the two additives present. Cases have been experienced with additive oils where soluble metal contents have given misleading results because of the presence in the " Sterimat "-filtered oil of colloidally dispersed metal sulphate.

The total base number (TBN), which obviously depends upon the type of additives involved, is also determined as an indication of unchanged additive. The ASTM electrometric method D-664 is frequently used, but a back titration of excess mineral acid, after acidification of the oil, to either an electrometric or indicator (pH4) end point, is preferred. With an additive in which the metal content and the TBN are equivalent the TBN on the used oil often gives a better indication of unchanged additive than does the metal content, since it is not affected by colloidally dispersed metal sulphate. On the other hand, errors may be introduced by the presence of soluble wear products (*e.g.*, soaps of oil-oxidation acids) which react with mineral acid.

Some time has been devoted, it is felt quite justifiably, to the consideration of methods for the analysis of used additive oils. The attraction of obtaining, inexpensively, information on the condition of an oil is as great with an additive oil as with any other oil. All the limitations listed above have, however, been encountered, and experience shows that it is only by studying the analytical data in the light of a full knowledge of the types and characteristics of the additive involved that conclusions of significance can be drawn.

Used-oil Analysis to Elucidate Field Problems

The engine problems which require improved lubricants for their solution usually involve either excessive engine wear or excessive deposit formation.

Problems Involving Excessive Wear

Engine wear may result from three basic causes :—

(i) corrosion caused by chemical attack on working surfaces by corrosive products of fuel combustion or oil oxidation;

(ii) abrasion caused by dust, solid particles, etc., which enter the engine with the induction air, or are formed as a result of the combustion of certain metal-containing fuels (*e.g.*, residual fuels);

(iii) erosion arising from metal-to-metal contact.

Cylinder walls and piston rings are the parts most susceptible to wear, but the conditions which affect their wear also affect, not necessarily in the same way, wear of other parts, *e.g.*, bearings.

Where engine wear is a field problem it is necessary to identify its cause, since different treatments are required to eliminate each main type. In any engine an idea of the likely extent of wear can be obtained from the total iron and bearing-metal contents in representative oil samples taken from the engine while operating.

Some relative indication of the contribution to total wear by abrasive wear can be obtained by examination of the benzene-insoluble portion of

the oil-insolubles. Road dust will normally be identified by the presence of silica in the deposit. The contribution of abrasives from the fuel can be gauged by analysis of the insolubles for metals present in the fuel. The effect of abrasive wear products (*e.g.*, iron) on wear itself will also be shown up by the iron content of the oil-insolubles. Abrasive wear must be largely combated by efficient air and oil filtration.

Corrosive wear in C.I. engines arises chiefly from attack of condensed sulphur oxides formed as a result of fuel combustion, and therefore depends to a large extent on the sulphur content of the fuel. The presence of sulphuric acid which has been found adsorbed upon the insolubles in used oils from C.I. engines, or of iron sulphates, can readily be shown by oil-analysis. Corrosive wear of piston rings and cylinder-walls is increased under engine conditions fostering low cylinder-wall temperatures, conditions which increase acid condensation and blow-by and therefore oil contamination. Thus, high wear in a highly contaminated oil (high soot and water contents, etc.) would be expected to have a large contribution from corrosion. Corrosive wear caused by strong acids, *e.g.* H_2SO_4, can be countered by neutralizing the acids with basic additives. Abrasive wear will not be reduced by such additives although wear by erosion may be.

After the introduction of an oil containing a basic additive into the engine under examination, a continuous study of the total base number and total iron content of the oil will give good indication of how completely corrosive wear is being combated.[6]

The corrosion of alloy bearings, *e.g.*, copper-lead, is largely caused by attack upon the lead by weak organic acids (*e.g.*, oxidation products) in the presence of peroxides.[7] Loss of copper is usually attributed to attack by inorganic acids. This type of bearing wear can usually be ascertained by metallurgical examination, and its cause can be examined by oil analysis. Excessive oil oxidation, which leads to corrosivity towards lead, cadmium, etc., will be shown by the presence of a high oil-soluble contamination which might well have arisen because of high concentrations of catalytic metals, *e.g.*, copper. The contribution of fuel oxidation acids to bearing corrosion cannot easily be determined.

Problems Involving Excessive Deposition

The elucidation of problems of excessive deposition is best achieved by analysis of the troublesome deposit.[8] If engine deposits can be removed for analysis, then used-oil examination will play a very minor role. Its chief contribution will be, in fact, in assisting in the interpretation of the results of deposit analysis. It is not always easy, however, to obtain samples of engine deposits, and in such cases attempts must be made to deduce from used-oil analyses (the samples for this being readily available in most cases) the probable nature of a deposit. This can rarely be achieved with certainty, but at least some useful indications can be obtained.

The type of examination which would be useful in this case would be an examination of the amount and nature of the suspended matter in the used oil. Abnormally large amounts of suspended matter would suggest that combustion conditions in the engine were poor, and that the deposition of insolubles as sludge may be the cause of the trouble. This latter cause of deposition would also be likely if the suspension of the insolubles in the

used oil were unstable and tended to settle out. This tendency can be determined by microscopic examination of the used oil.

The reasons for the formation of other types of deposit would be harder to assess. Excessive oil oxidation which would be indicated by viscosity measurements on the clarified oil or by direct oil-soluble contaminant measurements must be considered as a likely cause of deposit formation.

Used-oil Analysis in the Development and Use of Engine Tests

Development of New Engine Tests

Laboratory engine tests are designed to stress some particular aspect of field service rather than to reproduce the general field performance. This is necessary if laboratory tests are to be of reasonable duration, but in designing these accelerated tests care must be taken to ensure that the particular property is being assessed realistically and as specifically as possible.

The contamination of an oil is extremely sensitive to engine operating conditions, more so in fact than to oil quality. At the same time, however, in assessing, say, the anti-flocculating properties of an oil the quantity of insolubles to be held in suspension is important. Therefore in assessing the detergency of an oil for some particular field application the quantity of insolubles produced in the test engine should not be too far removed from that in the field. Analysis of oils from the laboratory test provides a very easy check of whether or not the newly developed engine test is assessing this specific oil property realistically, and at the same time, based on field data, may suggest a reasonable duration for a test under the conditions already determined.

This approach to the development of engine tests seems worthy of much greater consideration than has been given in the past. The concentration of contaminants in a used crankcase oil does not increase with time, but tends to an equilibrium value because of the influence of oil-consumption and make-up oil additions.[9, 10] Average figures for the contaminants in engines under service conditions have been quoted elsewhere.[3] In this laboratory, assessment of oil-soluble contaminants for a number of field engines gave average figures of 1 to 2%w for gasoline engines even under high-temperature conditions, and between 1 and 5%w for C.I. engines. Even for aircraft engines under very high-temperature conditions values are usually about 3%w and none over 6%w has been encountered. In the CRC L.4-545 test, however, values up to 15%w have been encountered. This latter test would appear to be very far removed from field experience, and certainly does not assess oil stability under realistic conditions.

The Use of Established Engine Tests

In an engine test which has been established for evaluating a specific oil property, all oils will be evaluated with respect to this property under identical engine conditions. However, these conditions do not necessarily imply equal oil contamination. Thus, for example, in the case of detergency tests in C.I. engines it is as well to check periodically that the input of insolubles into the oil has remained reasonably constant from test to test.

Rogue tests do occur, and can often be attributed to a wide divergence from the general level of contamination.

In tests on additive oils the depletion of an additive throughout a test can well be studied, as it may often indicate reasons for poor test repeatability. Again referring to the CRC L.4-545 test, wide variations have been observed in repeat tests in the rates of depletion of basic additives, also in the quantities of oil-soluble contaminants present and in the quantities of oxidation catalyst (copper, iron) present. Such variations, which occur in tests run under specified conditions, are very significant when the conditions for oil oxidation are considered, and may well account for the poor repeatability of the test.

SECTION VI. THE USE OF RADIOACTIVE-TRACER TECHNIQUE IN THE WEAR-TESTING OF ENGINE LUBRICATING OILS

By A. Dyson * and K. R. Williams *

Introduction

One of the most important properties of an engine lubricant is its ability to reduce engine wear; unfortunately this property is one of the most difficult to assess in short-term laboratory engine tests. Wear of the cylinder bores is the most important criterion in practice, and this is usually measured by the increase in maximum bore diameter. Very sensitive measuring techniques (*e.g.*, the Talysurf surface measuring machine) permit the detection of the minute changes in bore diameter which occur in quite short periods. The bore wear so determined has been found to vary with time in a rather irregular manner, and in practice it is necessary to run for a few hundred hours before a reliable measurement of bore wear may be made.

In many laboratories piston ring weight loss has been used with success for estimating wear over short periods in certain diesel engines, and has given good repeatability and good correlation with bore wear. However, the process of dismantling the engine and weighing rings is unsuitable when it is wished to study how the anti-wear performance of an oil varies with time. In gasoline engines excessive wear may occur for a considerable period following ring cleaning and engine reassembly. Since this excessive wear is also subject to appreciable variation, a large part of the wear recorded during a short-term test occurs under very artificial conditions, and the conclusions drawn may be quite misleading.

Chemical analysis of the crankcase lubricating oil for iron is useful, but its range of application is rather limited. The method is not sufficiently sensitive for use on short runs, and on long runs the corrections for oil consumption and make-up, and for fuel dilution, etc., become important, and may give rise to serious errors or reduce the sensitivity of the results. Furthermore, the source of the iron is uncertain; oil-soluble acids may attack iron surfaces anywhere in the engine, while some fuels contain con-

* The Shell Petroleum Co. Ltd.

siderable quantities of iron. An accurate iron balance is very difficult to achieve. A further disadvantage is the inevitable delay before the results of the analyses become available.

The radioactive-tracer technique offers a method of overcoming some of these disadvantages. Much of the development of this technique at Thornton has been carried out on a gasoline engine. The general technique is equally applicable to diesel engines and to the measurement of bore wear. This method of wear measurement has also been applied in the U.S. to the study of piston-ring wear in diesel [11] and in gasoline [12] engines.

Outline of Procedure

A cast-iron piston ring is irradiated for a period of four weeks in the neutron pile at the Atomic Energy Research Establishment, Harwell. After a period of three to four weeks to allow the short-lived radiations from impurities in the cast iron to decay, the ring is fitted to the top groove of an engine, with the help of special tools. When the engine is run, wear products from the top ring are washed into the crankcase lubricating oil, samples of which are taken at convenient intervals (every hour or every 2 hours) and assayed for radioactivity by means of a Geiger counter, which gives a counting rate proportional to the concentration of active wear products in the oil, *i.e.*, to the top-ring wear. After the sample has been counted it is returned to the engine and allowed to mix thoroughly with the remainder of the oil before the next sample is taken. Corrections for radioactive decay and for oil consumption, etc., must be made to the observed sample activities, but they are unimportant for runs of up to twenty to thirty hours duration.

Typical Results

Some typical results are given in Figs 2 to 4 in the form of graphs of cumulative top-ring wear, estimated in arbitrary units from the radioactivity measurements, against engine running time. Each figure refers to a different ring with a different history of exposure in the pile, and the arbitrary units have different values in terms of milligrams of weight loss for each ring.

For the first four days' running in Fig 2 the jacket temperature was 80° C, and the steady wear rate was very low—approximately 0·1 mg/hour. The wear rate during the first 2 hours after restarting was always considerably higher than during subsequent running, and this is attributed to warming up. Although the jacket coolant was heated to 80° C before the engine was started, the rubbing surfaces had not attained their working temperature. Before the start of this test the ring was removed and replaced, and as a consequence the wear rate was exceptionally high for the first few hours of operation.

After the fourth day (32 running hours) the jacket temperature was reduced to 30° C, with the result that the steady wear rate increased by a factor of approximately 10. This shows the importance of low jacket temperatures in producing severe corrosive wear, at least in gasoline engines. The effect of adding very small quantities of experimental anti-

wear additives to the sump oil while the engine was still running is also shown in Fig 2.

Fig 3 shows the very severe wear occurring in the first few hours of running-in a ring. This run was made at high jacket temperature and low load in order to reduce the wear as much as possible. The second run in

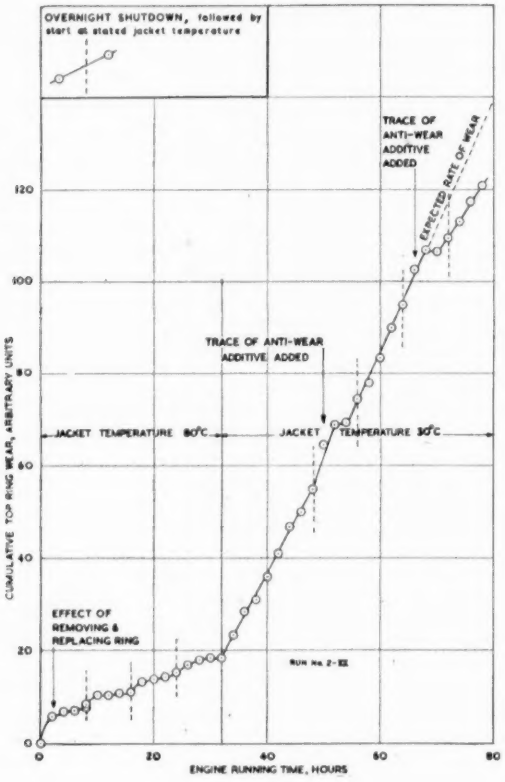

FIG 2

EFFECT OF (*a*) DROPPING JACKET TEMPERATURE FROM 80° TO 30° C; (*b*) ADDING A TRACE OF ANTI-WEAR ADDITIVE; (*c*) REMOVING AND REPLACING RINGS; (*d*) SHUTTING DOWN OVERNIGHT, WITH SUBSEQUENT WARM-UP

Fig 3 shows the effect of adding a rather larger quantity of anti-wear additive to the crankcase oil.

Fig 4 shows the increased wear after cleaning the ring and re-assembling the engine. It is thought that a cleaned ring is more liable to corrosive attack than a ring which has been run in an engine for some time. Fig 4 shows also the effect of adding, first a very small quantity, then a somewhat larger quantity of another anti-wear additive to the sump oil.

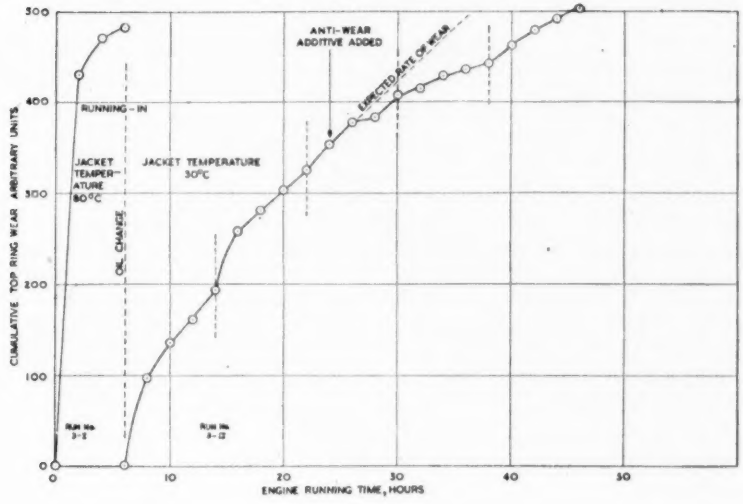

FIG 3

EFFECT OF (*a*) RUNNING-IN A NEW RING, AND (*b*) ADDING ANTI-WEAR ADDITIVE

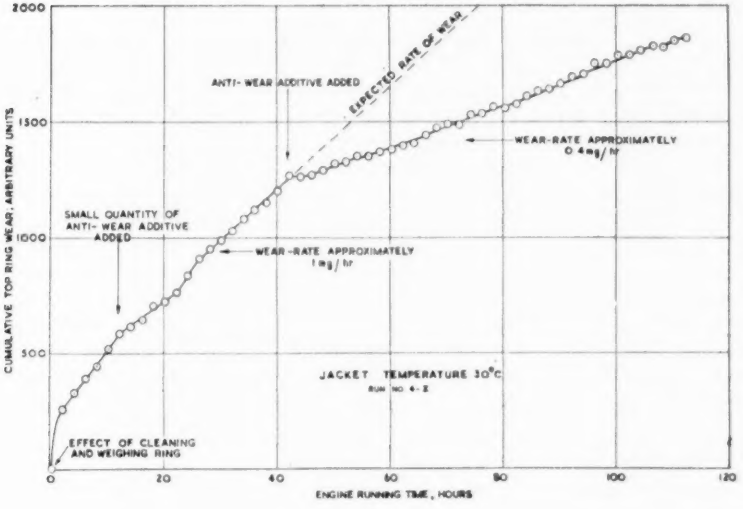
CUMULATIVE TOP RING WEAR, ARBITRARY UNITS
ENGINE RUNNING TIME, HOURS
ANTI-WEAR ADDITIVE ADDED
EXPECTED RATE OF WEAR
WEAR-RATE APPROXIMATELY 0·4 mg/hr
SMALL QUANTITY OF ANTI-WEAR ADDITIVE ADDED
WEAR-RATE APPROXIMATELY 1 mg/hr
JACKET TEMPERATURE 30°C
RUN NO 4-E
EFFECT OF CLEANING AND WEIGHING RING

FIG 4

EFFECT OF (*a*) CLEANING AND WEIGHING RINGS, AND (*b*) ADDING ANTI-WEAR ADDITIVE

Experimental

A brief description of the engine and operating procedure follows. The experimental details which are peculiar to this method of wear measurement are also covered.

Engine

The engine was a small industrial vertical single-cylinder liquid-cooled four-stroke gasoline engine, with a bore and stroke of about 3 inches. It was normally run at a speed of 1100 r.p.m. with a b.m.e.p. of approximately 47 p.s.i. The sump oil charge was approximately 2000 ml, and weighed oil samples containing approximately 700 ml of oil were run into the annular space between two concentric glass cylinders of radii 1·25 and 4·0 cm. The taking of an oil sample is illustrated in Plate I. The Geiger counter was inserted into the inner cylinder and the whole placed, for counting, inside a lead container with 1-inch walls.

Electronic Equipment

A 20th Century Electronics type G.10 Pb γ-sensitive Geiger counter with a lead cathode and thick glass envelope was supplied with an input of 1160 volts from an electronically stabilized power unit. The output from the tube was fed via a pre-amplifier into a scaling unit type 200, both constructed at Thornton from Ministry of Supply designs.

Health Precautions

The β radiation from the ring, being readily absorbed by matter, is normally screened by the cylinder block, and the minimum safe distance for continuous working is then approximately 2 ft. The danger from direct radiation is therefore small, except during such operations as cleaning and weighing the ring and assembling the engine. Special tools are used for these purposes, and Plate II shows the assembly process. An Ekco radiation monitor type 1118A is used to measure dosage rates, and can be seen in the photograph. Film badges are worn by all persons with duties in the cell, and the safety of the technique is demonstrated by the fact that the highest fortnightly exposure recorded over a period of more than twelve months has been one-fifth of a human tolerance dose for continuous working. Any possible absorption of active material into the body is prevented by the wearing of gloves and eyeshields when handling oil samples, and by common-sense cleanliness and tidiness in the cell. Blood counts are taken periodically as a precaution against any ill effects.

Activity Induced in the Ring

The rings were normal plain cast-iron rings to 4K6 specification without phosphide coating, and contained 0·5%w phosphorus, 1·0%w manganese, and 0·35%w chromium. They were irradiated for four weeks in the neutron pile at a flux of (6 to 8) $\times$ 10^{11} neutrons/sq.cm/sec. When the rings are first removed from the pile, the small amount of manganese present gives by far the strongest radiation, but its half-life is short, and it

PLATE I

TAKING AN OIL SAMPLE

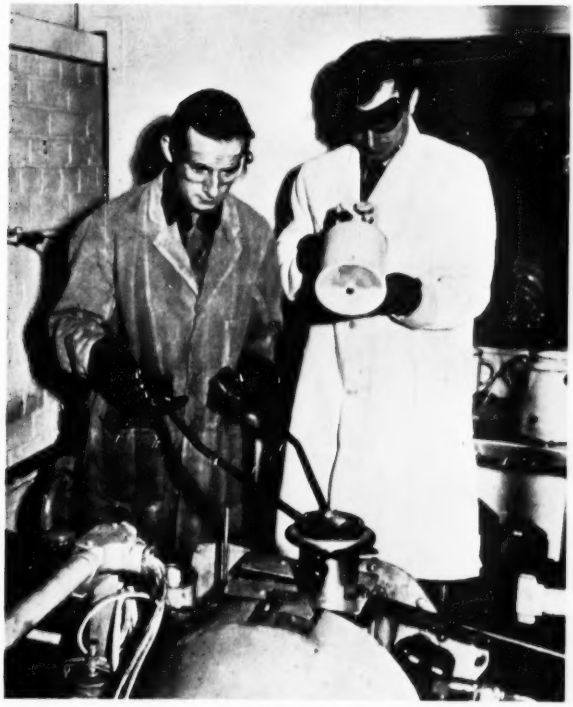

PLATE II

FITTING A RADIO-ACTIVE RING TO THE PISTON

[To face p. 528.

decays quickly. There is a further unidentified activity with a half-life of two to four days, and this is therefore allowed to decay for twenty to thirty days. After this time the main β activity originates from the P^{32} and Fe^{59} isotopes, and the γ activity from Fe^{59} and Co^{60}.

The phosphorus is concentrated to a large extent in the grain boundaries, and is therefore irregularly distributed, whereas the cobalt is in solid solution in the ferritic or pearlitic matrix. To obtain a counting rate proportional to the concentration in the oil of iron worn from the top ring, it is therefore necessary to count γ-rays. Unfortunately the Geiger counter responds far less efficiently to γ-radiation than to β-radiation, so that a counting efficiency considerably lower than that for a β counter must be accepted. The Fe^{59} activity is approximately 56 microcuries/g, or a total of approximately 1 millicurie. A larger ring or sleeve could not be accommodated in that part of the pile with the most intense nectron flux, and the specific activity would be of the order of one-tenth that quoted above for the ring. It would then be necessary to use a more sensitive method of detection in order to obtain adequate accuracy.

Decay Corrections

The observed sample activities must be corrected for radioactive decay in order that results of different runs may be compared, and also in order to calibrate the method, as explained in the next section.

For this purpose some oil samples are retained and counted at intervals of a few days while the ring is in use. After such a sample has been allowed to rest undisturbed for a few weeks, vigorous stirring and repeated decanting does not change the counting rate, and it is concluded that sedimentation does not introduce any errors. The plots of logarithms of activity against time are curved, owing to the presence of two activities, Fe^{59} and Co^{60} with half-lives of forty-seven days and five years respectively. A straight line may be obtained by plotting the activity against the quantity $(\frac{1}{2})^{t/47}$, where t is the time in days after the ring has been removed from the pile. The Co^{60} activity is assumed to be constant during this time. The best lines are fitted to the experimental points, and are used to refer the observed sample activities to a standard time. The counting rate due to the cobalt isotope was found to be approximately 7% of the initial counting rate due to the iron, although the concentration of cobalt was estimated at only 0·076%w by chemical analysis.

Calibration and Estimate of Consistency

It is possible to estimate the actual ring weight loss corresponding to a given counting rate, but the approximation is rather wide, and it is preferable to calibrate directly. This is done by weighing the ring before and after a series of runs. The total wear is estimated in arbitrary units from radioactivity measurements, after correction for decay, oil consumption, and make-up. In correcting for oil consumption it is assumed that the oil consumed carries with it a quantity of active material equal to the product of the volume of oil lost and the concentration of active material in the bulk oil. Some typical results are given in Table II.

TABLE II

Calibration in Terms of Ring Weight Loss

Hours run during period	Top ring weight loss during period, mg	Total wear during period, arbitrary units	Ratio arbitrary, units/mg
24	53·5	1270	23·8
46	59·7	1590	27·4
54	55·1	1310	23·8
188	144·6	3870	26·7
184	181·1	4870	26·9

There is a scatter of a total range of approximately $\pm 7\frac{1}{2}\%$ about the mean ratio.

Sensitivity of Wear Detection

One milligram of top ring wear will give a counting rate of approximately 45 counts per minute above a background of 30 c.p.m. with the particular experimental arrangements used. Starting with clean oil, the minimum wear which can be detected at the 95% confidence level in a 60-minute count is 0·04 mg, equal to a concentration of 0·02 ppm of iron in the oil. The greater the concentration of active material already present in the oil, the less accurate is the estimate of increments of wear over a short period. If 10 mg of active iron is already present in the oil, the 95% confidence limits of wear occurring in a further short interval are approximately $\pm 0{\cdot}17$ mg.

CONCLUSIONS

The radioactive-tracer technique enables accurate measurement of engine wear to be made at short intervals without stopping the engine and without delay in the availability of the results. Furthermore, it is possible to observe immediately the influence on wear of any change in operating conditions. It is most useful for following details of the wear process over runs of comparatively short duration—up to 40 to 50 hours, depending on the wear rate.

The technique is being used at Thornton Research Centre for studying piston ring wear both in gasoline and in diesel engines. It is hoped to study cylinder wear using an activated sleeve. Unfortunately interesting bearing materials, such as copper and lead, are not suitable for use by this method, although the entry of small quantities of lead into the lubricating oil may be detected by incorporating 1 to 2 per cent of thallium as solid solution in the lead.

SECTION VII. SOME APPLICATIONS OF STATISTICAL TECHNIQUES TO THE ENGINE-TESTING OF LUBRICATING OILS

By R. Smith * and K. R. Williams *

Introduction

The necessity for engine testing of H.D. lubricating oils has been established as a result of the inability of other physical and chemical tests to predict the performance of lubricants in engines. However, an internal combustion engine is a complicated apparatus which is subject to the effects of many variable factors which are often extremely difficult to control with sufficient accuracy to produce satisfactory repeatability of results. Because of the difficulties encountered in running satisfactory engine tests, much time and thought have been given to the control of operating variables in order to allow testing to be carried out according to the classical methods normally used with simpler laboratory apparatus. These methods when applied to engine testing fail to elucidate the complex interactions † between the many factors affecting engine performance and the criteria by which the performance of lubricants are judged. Hence, the search for more suitable engine testing methods has been vigorous.

There are two aspects of oil evaluation in which statistical techniques are of considerable value. First, in the development of oils and additives it is often necessary to know whether one product is better than another, or whether a change in operating conditions (*e.g.*, jacket temperature) affects the performance of an oil. Statistical methods can suggest the most economical way of running such experiments, and when applied to the results can advise the experimenter of the existence of significant differences or otherwise. The other aspect of lubricating-oil evaluation is that in which standards of performance are established which must be met by a product before it is accepted as satisfactory. The problems involved in selecting such tests from the point of view of practical significance have already been dealt with in Section I, and the arguments which follow assume that any test which is chosen for specification testing takes full account of such considerations.

The Case for Statistical Techniques

No one would seriously dispute the statement that experimental results are subject to error. This fact is, however, often overlooked when assessing the merits of lubricating oils from the observed results of engine tests. Results are often misinterpreted because of this oversight, and it is quite common for conclusions to be drawn from totally inadequate data.

No difficulty should arise in specifying a simple physical property (*e.g.*, density) of an oil, since it is readily measured with apparatus which may be standardized at a central point. The situation is by no means as simple

* The Shell Petroleum Co. Ltd.

† Two factors are said to interact if the effect of a given change in one factor depends upon the value of the other.

in the case of engine performance. No two engines are identical in performance, even when installed in identical situations, and their performance also changes with use—*i.e.*, in the process of evaluating an oil the test equipment changes. This means that both variations within and between laboratories can be expected, and a useful application of statistical techniques is in assessing the variations encountered in such tests. For a specification test to be useful, it must take full account of such variations. Usually such a test will include some lower limit of performance, and it is important that this standard should be set with due regard to the repeatability and reproducibility of the test. In the case of engine cleanliness, for example, unless the test conditions are very closely repeatable it is unwise to choose running conditions so that the standard of acceptance demands a very clean piston. If too high a standard of cleanliness is chosen it may well be that an oil which passes the test once may subsequently fail on several repeat tests, or alternatively an oil which would, on the average, fail, may be passed by sufficient repetition of the test. A test of this nature can be a source of embarrassment to the oil supplier, who can never be certain that an oil which passed " with flying colours " when tested would not fail if tested again. From a statistical point of view a suitable test for engine cleanliness might demand the production of say two pistons run under test conditions which gave a slightly dirty piston with an oil of acceptable quality. For example, in a test of the type described in Section II using a Gardner engine two pistons having a mean rating of not less than 8 might be demanded. The operating conditions (including test duration and fuel) specified in such a test could be chosen to give such a standard of cleanliness with an oil having the required level of performance.

The possibility of drawing wrong conclusions from test results can be illustrated by the data given in Table III, which represent piston-cleanliness

TABLE III

Piston Cleanliness Ratings on Different Oils in Two Engine Tests

Test A .	5·8	4·5	8·3	7·5	8·6	4·7	4·4	5·1	4·3	3·5	4·0	9·2
Test B .	6·5	5·2	8·9	8·4	8·9	6·8	6·6	4·9	5·1	4·3	4·1	8·6

ratings obtained on a number of different oils from two different engine tests. Engine test A is a lengthy and costly test to run. Engine test B is a short duration test which is relatively inexpensive compared with test A, and was therefore used to " screen " oils before subjecting them to test A. Inspection of the data indicated good correlation between the two tests, and it appeared that test B could be substituted for test A. However, a statistical analysis of the results showed that, although correlation between the two sets of ratings was highly significant, the accuracy with which a result of test A could be predicted from a result of test B was totally inadequate. A difference in rating of at least 1·7 would be necessary for single tests on different oils in test B to show up in the same order in test A with 95% confidence. It is submitted that inspection of these data and induction alone would not reveal the true state of affairs.

Despite the fact that it is often possible to obtain correlation between

laboratory engine test results and field results, experience has shown that this does not necessarily mean that field performance can be predicted from test results obtained in the laboratory. The use of statistical methods can at least provide information concerning the confidence with which conclusions are drawn from correlation data and so reduce the chances of making wrong decisions.

The need for good reproducibility of engine test results is universally acknowledged, but the methods used for assessing it are often lamentably weak. It is usual for experimenters to compare results with respect to those of a reference oil which is tested periodically. The test reproducibility can then be determined from the reference-oil tests, and testing may be continued until the reproducibility is considered unsatisfactory. However, this practice takes no account of possible differences in repeatability at different performance levels, and when this is realized it is usual for references at " high " and " low " levels to be adopted. This device improves matters, but is wasteful in engine running time and does not deal with the fundamental problem set by the effects of interactions between factors which affect engine results. A more satisfactory procedure is to repeat each engine test and thus provide data from which a reliable indication of test repeatability can be obtained and from which " rogue " results can be detected by making further tests when excessive variance is exhibited between repeated tests. The engine running time required for each lubricating oil rating is at least doubled by this testing technique, and its use is only justified in terms of precision of determination. If the test repeatability is consistently good, repeat testing is obviously not necessary except for occasional checks. Unfortunately, engine running time is often scrutinized more closely than engine test repeatability, and as a result test variance is often under-estimated. In one such case in a lubricating-oil test, a statistical analysis of cylinder-wear data revealed that the 95% confidence limits for a single determination were $\pm 80\%$ of the maximum permissible wear in this test. Thus, if an oil passes the test on one occasion there is no guarantee that it will pass if the test is repeated.

Some Applications of Statistical Techniques

The determination of the relative anti-wear characteristics of lubricating oils is probably the most difficult of engine testing problems. The nature of wear tests is such that some of the important factors affecting wear are themselves affected by the wearing process. Indeed, the eventual replacement of engine components, such as piston rings and cylinder liners, leads to changes in the wear characteristics of the engine which are often greater than the effects of the lubricants being tested. These considerations suggest that wear determinations should be obtained in batches of a size determined by consideration of such factors as engine wear rate, types of lubricant to be tested, type of fuel used, and so on. It is in such applications that statistical techniques can be used to great advantage by enabling experiments to be designed so that the maximum information can be obtained from the minimum number of test runs, and in the case of wear tests, so that variations attributable to wear of components can be randomly distributed in such a manner that results are not biased by its effect.

With suitably designed experiments it is possible to estimate the effects of factors which are not amenable to accurate control and to discern when the combined effects of factors are important in relation to the error inherent in the engine test. A series of experiments carried out in a single-cylinder, direct injection, compression ignition engine will serve to illustrate these considerations.

A testing procedure had been developed in this engine which was intended to assess the relative anti-wear characteristics of H.D. lubricating oils, but in some initial trials differences were shown between engine piston assemblies. A small experiment was then made using two lubricants and another two piston assemblies. The results obtained are given in Table IV.

TABLE IV

Ring weight loss, mg	Assembly " A "	Assembly " B "
Oil 1	142·9 125·1 124·1	96·5 140·0 —
Oil 2	212·1 239·1 211·5	131·4 261·1 —

Inspection of these data reveals a difference between the two lubricating oils, but it is difficult to decide whether a piston-assembly effect exists. Statistical analysis has shown that no significant difference in wear can be attributed to piston assemblies on the basis of these results. It can also be shown that a difference between lubricants could not be claimed with 95 per cent confidence until three tests had been run on each oil with piston assembly " A "; it was for this reason that the two extra tests were made with piston assembly " A."

The accuracy with which wear can be determined in engine tests is notoriously poor, and in this case it can be shown that if a single result yields a value x it may be asserted that the true mean of a large number of replications will lie between $0{\cdot}6x$ and $1{\cdot}6x$ in nineteen out of twenty cases (*i.e.*, 95 per cent confidence). This order of inaccuracy may appear to be excessive, but much experience has shown that it is quite normal for engine wear determination. The limits are narrowed as the degree of confidence with which the conclusions are accepted is decreased.

An experimental design which obviates the necessity for test replication is illustrated by Table V, which gives the total ring weight losses from a series of tests made to investigate the effect on engine wear of some lubricating-oil and fuel characteristics in the engine referred to in the previous table.

It is easy to observe the difference in piston-ring wear with the two fuels and with the two oil viscosities, but the effect of different oils is not quite so obvious. Statistical analysis of the results shows that the effect of fuels and of oil viscosity on wear were highly significant; the probability that these effects were obtained by chance is less than 1 in 1000. That oil 2 gave greater wear than oil 1 can be asserted with 95 per cent confidence, and it can be shown that an interaction between fuels and oil viscosities

TABLE V

Total ring wt loss, mg		F_1		F_2	
		P_1	P_2	P_1	P_2
O_1	V_1	276·4	280·0	42·0	49·6
	V_2	92·5	69·5	36·6	28·0
O_2	V_1	270·8	354·5	75·0	131·7
	V_2	118·9	102·9	48·7	38·2

where O_1 and O_2 are two straight mineral oils from different sources;
V_1 and V_2 are low and high oil viscosity respectively;
F_1 and F_2 are two distillate fuels from different sources;
P_1 and P_2 are different piston assemblies.

was significant; the decrease in wear with fuel No. 2 (F_2) was greater when using the lower viscosity oil than when using the higher viscosity oil. Another interesting feature shown by the statistical analysis is an interaction between oil viscosities and piston assemblies. That one piston assembly reacted differently to the lower oil viscosity than the other can be asserted with very nearly 95 per cent confidence. A second-order interaction between oil viscosities, fuels, and oil types was relatively large, but not significant at a suitable confidence level (95 per cent is usually accepted). For this reason it is considered inadvisable to utilize this type of factorial experiment for wear investigations, as it is not entirely suitable for dealing with data which involve interactions of a high order relative to the number of factors considered.

A more satisfactory factorial design is shown by Table VI, in which three factors are each considered at three levels. Wear determinations have

TABLE VI

Total ring wt loss, mg		S_1	S_2	S_3
V_1	C_1	18·2	18·0	85·9
	C_2	14·7	9·3	30·2
	C_3	27·0	29·1	15·3
V_2	C_1	23·1	17·6	91·5
	C_2	16·4	8·7	59·8
	C_3	11·5	13·2	26·1
V_3	C_1	24·0	57·4	105·3
	C_2	24·9	39·7	55·1
	C_3	11·0	20·8	18·3

again been chosen for consideration, but other criteria of lubricating-oil performance, including piston cleanliness, were obtained. The three factors investigated were lubricating-oil viscosity (V), lubricating-oil additive concentration (C), and fuel sulphur content (S). The different levels of sulphur and oil viscosity were in arithmetic series, and those of additive concentration in geometric series. The oil viscosity and additive concentrations were not chosen to represent currently marketed oil formulations,

and the range of fuel sulphur content was greater than would be met in practice in the U.K.

This experiment was an outstanding illustration of the complex nature of the factors affecting wear in engines, and showed the futility of assigning values to independent effects of single factors without due regard to the many significant interactions between these effects. The analysis of the results showed two significant main effects and six significant interactions, four of which contained quadratic components. The conclusions drawn from the results were :—

(1) except with the highest viscosity oil, no significant difference in wear was shown between the two fuels of lower sulphur content (S_1 and S_2 containing 0·2 and 1·0%w sulphur respectively);

(2) with oils of all three viscosities and of the two lower additive concentrations wear was greatest with the fuel of highest sulphur content (S_3 containing 1·8%w sulphur);

(3) the decrease in wear rate with increase in concentration of the lubricating-oil additive was significantly different at each of the three viscosity levels, *e.g.*, the highest viscosity oils (V_3) exhibited a greater decrease in wear with increase in additive concentration than the lowest viscosity oil (V_1);

(4) wear rate decreased slightly with increase in lubricating-oil viscosity when using the highest additive concentration and increased when using the two lower additive concentrations;

(5) the relation between oil viscosity and wear when using the fuel containing the intermediate sulphur content differed from those relations obtained with the other fuels;

(6) the relations connecting wear with fuel and sulphur content varied significantly with lubricating-oil viscosity.

The advantages of using statistically designed experiments for the investigation of such parameters as engine cleanliness, lubricating-oil consumption, etc., are apparently not so great as for wear problems because interactions between major factors are not so common. However, a designed experiment which shows no significant interactions between factors can be of great service. It is just as important to know of their non-existence as it is to know when they do exist.

In the experiment represented by Table VI certain engine cleanliness data were obtained. These are given in Table VII and, when analysed,

TABLE VII

	S_1			S_2			S_3		
	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3
V_1	8·9	8·5	9·7	7·3	9·2	9·6	4·8	8·0	9·3
V_2	8·8	9·1	9·8	8·8	8·7	8·3	4·8	8·5	9·1
V_3	9·0	9·4	9·2	6·8	8·5	9·0	5·3	6·3	8·9

reveal a significant change in cleanliness with increase in lubricating-oil additive concentration. An interaction between additive concentration

and fuel sulphur content is also shown. The effect of additive concentration is greater with fuel of high sulphur content than with fuel of low sulphur content. No other factor or interaction between factors had significant effect. The absence of effects attributable to differences in lubricating-oil viscosity were probably more important than the two significant effects.

It is generally more difficult to obtain significant data from field tests than from laboratory experiments, and statistical methods can be used to decide the most satisfactory form for experiments in the field. Under ideal conditions this approach is similar in application and interpretation to that used in laboratory testing. Frequently, in the case of test programmes of long duration, through circumstances beyond the experimenter's control (*e.g.*, accidents to vehicles involved), certain tests are not completed. Although this may limit the amount of information obtained from the experiment, the data may still be statistically analysed. Such an instance is furnished by the data given in Table VIII obtained from a number of vehicles used in road haulage service.

TABLE VIII

Total Ring Wear for Road Haulage Vehicles

(g/10,000 miles)

Oil " A "	Oil " B "	Oil " C "	Oil " D "
1·21	1·10	0·83	0·55
1·20	1·30	1·17	0·62
1·40	—	0·77	0·81
—	—	0·97	0·65

Despite the absence of data from three vehicles, it can be shown that oil " D " gave significantly less ring wear than any of the other oils and that oil " C " was significantly superior in this respect to the mean of oils " A " and " B " together.

All the conclusions drawn from the data in Tables VI, VII, and VIII are submitted with *at least* 95 per cent confidence. The chances of being misled by these data are therefore 1 in 20 at the most.

It is beyond the scope of this paper to discuss more than a very small number of the possible ways in which statistical design and analysis can aid in the engine testing of lubricating oils. The aim has been to introduce, rather than to discuss, statistical applications, and no attempt has been made to deal with the theories involved or the methods of analysis used.

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LUBRICATING OIL REQUIREMENTS FOR PASSENGER TRANSPORT AND LONG-DISTANCE HAULAGE WITH COMPRESSION-IGNITION ENGINES

By A. T. Wilford * (Fellow)

It is generally agreed that it would be difficult, if not impossible, to design an engine test in which were faithfully reproduced the variations in speed, load, and other conditions encountered by an engine when running in service. Even if the difficulties could be overcome, such a test would find little favour for assessing the suitability of a lubricating oil, for the reason that its duration would be far too long. The length of the test would in fact be a measure of the quality of the oil. But this is just the criterion by which an operator of C.I. engines assesses the quality of a lubricating oil; there is only one requirement—that the oil shall enable engines to run for the longest possible time before having to be withdrawn for overhaul. Considerable care is exercised in selecting oils which meet this requirement, and, as will be shown later, the service tests must be properly planned and are likely to be protracted. But having made the selection, it is necessary to ensure that subsequent supplies will continue to give the desired performance in service. If the selected oil is of the non-detergent type it is possible to compile a specification based upon physical characteristics, and experience over the years has shown that, if correctly drafted, such specifications fulfil their object. Difficulties are immediately encountered, however, if an attempt is made to draft a specification for a detergent-type oil. It

* London Transport Executive.

may be suggested that these difficulties are more apparent than real and that the way out of the trouble is to adopt one of the recognized specifications such as MIL-0-2104 or DEF.2101. The reply is that neither of these specifications is based upon the requirements of British engines, and even if a particular oil meeting one or other of these specifications has been proved suitable in a particular application in road transport, an operator may be forgiven for wondering whether all MIL-0-2104 (or DEF.2101) oils would be equally satisfactory.

Before pursuing this subject further, it is appropriate to give an account of the way in which an engine lubricating oil is tested in service. The procedure varies no doubt according to both the size of the undertaking and the technical facilities it possesses; the details which follow relate to the test procedures which have been evolved over the years within London Transport.

London Transport's fleet is now entirely composed of C.I. engined vehicles and at the present time a detergent-type oil of SAE 20W viscosity is in use for both red and green buses and also for coaches. Alternative lubricants are tested in comparison with the " standard " SAE 20W detergent-type oil, and experiments with oils of lower viscosity and with a 20W " Supplement I " type oil are in current progress.

If the experimental lubricant is radically different from the standard oil, the service test is initially confined to a total of twenty-four vehicles of a particular type, fitted with newly overhauled engines and operated from one garage. Twelve of the engines are lubricated with the experimental oil, the other twelve constituting a comparison group in which the standard lubricant is used. The engines are distinctively labelled, so that they can be readily identified both at the garage and upon arrival, in course of time, at the central repair works for overhaul. If, during a period of about eighteen months, the proportion of early failures in the experimental group is not significantly different from that of the standard group, the scope of the test is extended.

If there is reasonable confidence that the experimental oil will have no detrimental effect on engine life, a large-scale test can be put in hand at once. The procedure for carrying out a test of this sort has been developed in co-operation with the statisticians, whose advice is sought at all stages, from the initial planning to the final analysis of the results. In principle, the test consists in determining the mean life obtained between overhauls from engines at two garages at which the experimental and standard oils are respectively in use. It is, of course, essential that the garage fleets are composed of engines and vehicles of the same type and that the duties performed by the vehicles at the two garages are comparable. This latter requirement, though fundamental, is more difficult to meet than might be imagined, in that no two garages are precisely similar, either in respect of routes operated or traffic and loadings encountered. These differences are reflected in fleet fuel consumption figures, which, due to causes that are not within the control of the engineers, may vary widely from one garage to another. These records, however, can be of assistance in selecting garages at which lubricating oil tests might be carried, for it is not perhaps unreasonable to assume that fleets whose fuel consumptions differ by no more than 1 or 2 per cent are performing comparable, if not similar, duties. After

eliminating garages at which fleet composition or routes operated are unlikely to remain stable over a period of three years or more, the choice will probably be reduced to two or three pairs. It is preferred to conduct the tests at two pairs of garages; by so doing, it is possible to obtain two independent estimates of the performance of the experimental oil, and at the same time to determine the precision of the result in that data concerning the performance of the same oil at two supposedly comparable garages will also be obtained.

The next problem which arises is that of the duration of the test. It will be appreciated that for a test in which 600 or more engines may be involved, it is impossible to start with newly overhauled units. At the commencement of the test, therefore, both the experimental group and that in which the standard oil is being used will be composed of engines in all stages of life, and only in course of time will the stage be reached at which all engines in the experimental group commenced life with that oil as lubricant. If it is necessary to wait until the great majority of these engines have failed, before attempting to assess their mean life in comparison with that of the standard group, an answer may not be obtained within a period of four years from the date upon which the test was started. During so long a time, operating and other conditions at the garages concerned are liable to change; there is, moreover, an urge to obtain an answer from the test. It has been found possible to reduce the length of the test by reviewing from time to time all available data concerning the lives of the engines involved, not only those which have failed but also those which are surviving, or for some reason or other may have been withdrawn from the test before failure. The data are sufficient in number to permit their being examined by a statistical technique analogous to that employed in actuarial calculations for measuring the length of human life. To explain the relevance of this technique, it need only be remarked that it is unnecessary to wait until the last individual has died before it is possible to compute the mean expectation of life in the population as a whole. From the statistical aspect, the two groups of engines are, of course, separate populations, each having its own mean expectation of life between successive overhauls. Estimates of mean life at any particular stage of the test are accurate within certain limits, which become narrower as time proceeds. The test can therefore be terminated when the results obtained are judged to be of sufficient accuracy. In practice, the use of this statistical method renders it possible to complete a test in from two and a half to three years.

The test procedure as a whole may seem to be elaborate and time consuming, but it must be remembered that, with a large fleet of vehicles, even a small extension of the life of engines between overhauls will lead to considerable financial savings and, conversely, selection of the wrong type of oil might prove to be a very costly mistake. It is necessary, therefore, to plan and conduct the tests in a manner such that the results can without question be accepted as being reliable. For in London Transport's experience, the increase in engine life to be obtained from a change in the type of lubricating oil is relatively small. Thus, when changing from a conventionally refined oil to one of the solvent refined type, the life of engines between overhauls was extended by about 11 per cent; when some twelve years later this solvent refined, plain oil, was replaced by a detergent type

lubricant, engine life was again increased, this time by rather less than 8 per cent. On both occasions substantial reductions in maintenance costs were effected, but in terms of engine mileage the gains were not sufficiently large to permit their having been confidently estimated without recourse to large-scale tests of comparatively long duration.

The specification which was compiled as a result of the service tests with solvent refined oil called for a lubricant within the SAE 30 viscosity range, of high viscosity index, and possessing exceptionally good oxidation characteristics. The detailed requirements, including drafting modifications subsequently introduced, are given in Appendix I(*a*). Over a period of years this specification has been adopted by many other operators of C.I. engines, both at home and abroad.

The specification is a restrictive one, and characterizes a type of oil which in course of time became extensively used as a base oil for H.D. type lubricants. When it became desirable to draft a " London Transport " specification for detergent type oil, it was only necessary to demand that the plain oil already in use should be blended with an approved detergent additive, the proportion of the additive to be such as to produce a lubricant equivalent to that called for by the then current U.S. specification 2-104B. Oils meeting this new London Transport specification were tested in service, with the result already mentioned. The specification was subsequently extended to include a base oil of similar type, but having a viscosity within the SAE 20W range; its characteristics are given in Appendix I(*b*). These specifications for detergent type oils of SAE 20W and 30 viscosities have been adopted by operators other than London Transport, and in particular by the Road Haulage Executive.

There will be no dispute that when blended with the requisite proportions of a detergent additive, base oils of the type detailed in Appendix I will yield H.D. oils capable of meeting the engine test requirements of the obsolete 2-104B or the current MIL-0-2104 and DEF.2101 specifications. These particular H.D. oils would also meet the service requirements of London Transport and certain other operators (though it is unlikely that it would be possible to differentiate between a 2-104B and a MIL-0-2104 oil under bus operating conditions). But acceptance of H.D. oils produced from these base oils cannot be regarded as an approval covering every oil which would meet the U.S. specifications. In support of this attitude it is relevant to quote from a paper by Joachim *et al* [1] dealing with tests on oils for the U.S. Navy. The statement is made that no physical, chemical, or bench tests can substitute full-scale, service type diesel engine tests in rating H.D. oils for their effective detergent properties.

It would, of course, be possible for London Transport or other operators to conduct service tests with H.D. oils of various make-up, but there are practical limits to the amount of such experimental work which can be done; there are many other calls upon technical resources and garage facilities. If, on the other hand, any oil complying with specification MIL-0-2104 is to be admitted, operators are forced into the position of agreeing that their lubricating oil requirements—relative to both engines and operating conditions—are correctly assessed by the performance of oils in the Caterpillar L.1 test.

In asking whether this position can be accepted, it must be remembered

that, as described by Rosen,[2] the Caterpillar test was originally developed for the purpose of selecting oils which would minimize the serious troubles due to ring-sticking, ring and piston scratching, piston deposits, and bearing corrosion encountered by Caterpillar engines in service when solvent refined oils were first introduced. No troubles of comparable severity have been met with in British engines, and many operators in Britain derived benefit from the adoption of solvent refined in place of conventionally refined oils. Even to-day, solvent refined oils of a non-detergent type are often preferred, not because operators are conservative, but because they do not encounter the troubles which detergent type oils are claimed to reduce. Where the latter type of oil has been adopted, the step has been taken after due consideration and not as a panic measure.

The Caterpillar L.1 test might therefore be criticized on the grounds that it employs an engine the characteristics of which are very different from those of British engines as a whole. On the other hand, there might well be difficulty in selecting as a test engine one of British manufacture and accepting it as typical of all British makes. Furthermore, the objection against the Caterpillar engine test would fall to the ground if it could be established that it is able to rate oils in the same order as they would be placed when tested under service conditions in British engines. So far as the author is aware no systematic tests have been carried out with the aim of comparing Caterpillar L.1 ratings with service ratings in British engines. Some attempt to establish a correlation between service performance and test engine rating was made by the Motor Industry Research Association [3] in the course of their endeavours to develop an accelerated test using a six-cylinder engine of British design. Amongst the reasons which led them to abandon this line of approach was the fact that their test did not reproduce the type of ring-sticking most commonly encountered in bus engines in service.

In the Caterpillar L.1 test the conditions are such that if ring-sticking occurs at all, it is the top compression ring which is the first to be affected, the trouble being progressively less with the lower rings. The same is true for carbon deposits in the ring grooves; the amount of deposit is greatest in the top compression ring groove and progressively less in the second and third ring groove. Any appreciable carbon filling of the scraper ring slots and of the drain holes in the scraper ring groove is most unlikely, and would certainly not be found with an oil which was accepted as meeting Specification MIL-0-2104.

This pattern of ring-sticking and carbon deposits does not correspond with that found in London Transport's engines when stripped for overhaul. As a generalization it can be said that in London bus engines the ring which gives the most trouble is the top scraper ring. Stuck compression rings are not unknown, though trouble with these rings has been much less prevalent following upon the adoption of detergent type oil. The incidence of top scraper ring sticking has also been reduced, but carbon filling of scraper ring slots and ring groove drain holes is still much in evidence. Piston skirts are heavily carboned, this being another point of difference from the Caterpillar engine, where, at the conclusion of the test, the piston skirt is discoloured, if at all, with a thin deposit of lacquer rather than of carbon.

The Caterpillar L.1 test is designed to simulate conditions of high loading

and high temperature, and it has been suggested that the lack of correlation between pistons from this test and those from bus service is indicative of a " cold running " engine in the case of the latter. This explanation fails to take account of the strenuous conditions under which the bus engine has to operate, nor is it supported by available data regarding the temperature of the sump oil and cooling water of the engines in service. Limited tests, comprising some 250 observations derived from ninety-four buses at various seasons of the year, have established that there is a linear relationship between sump oil temperature and atmospheric temperature. The relationship can be approximately expressed by the equation :—

$$y = 130 + 0{\cdot}5x$$

where y = sump oil temperature in degrees Fahrenheit;
x = atmospheric temperature in degrees Fahrenheit.

Thus, with an atmospheric temperature of 50° F (the mean annual temperature at Kew), the mean temperature of the sump oil in London buses would be about 155° F. Data relating to the temperature of the cooling water have been obtained from some forty service buses running on a typical route on both summer and winter days. With an ambient atmospheric temperature of 73° F, the mean temperature of the engine cooling water was 162° F; at 36° F, the mean temperature of the cooling water was 154° F.

It has also been suggested that whereas in the Caterpillar L.1 test, ring-sticking starts at the top of the piston and travels downwards, the reverse state of affairs, *i.e.*, ring-sticking from the bottom upwards, is typical of the bus engine. The difference between test engine and service conditions is, however, not quite so simple as this. In the first place, it is the *top* scraper ring which gives the most trouble in London bus engines, though, as already mentioned, sticking of compression rings is not unknown. It would seem likely that two separate factors are operating, one of which affects the top scraper ring, the other the compression rings; under normal conditions in London the former factor is the predominant one.

Information has been obtained about the incidence of piston ring sticking in buses operated by certain provincial companies. In general, but little trouble is experienced, and many of the operators are still using non-detergent type oils; where ring-sticking is encountered, it is sometimes the top scraper ring, and in other cases the compression rings, which are affected. The evidence strongly suggests that trouble with the top scraper ring is characteristic of engines operating on town services, whereas sticking of the compression rings is more likely to be met with in engines on long distance work. It is of interest to quote the experience of one particular company which advised that no ring-sticking was encountered with double-deck buses in town service but if, as was occasionally the case, the vehicles were used on long distance work, trouble was experienced with the top compression ring; it was added that the vehicles were rather low-geared and on the longer services had to operate at maximum revolutions for long periods.

Information has also been obtained in respect of the incidence of ring-sticking in engines in long-distance haulage vehicles operated by the Road

Haulage Executive. There is a general consensus of opinion that in this type of service—and the emphasis is on long haulage—the compression rings are the first to be affected ; stuck scraper rings are unlikely to be encountered unless the compression rings are also stuck. In the majority of cases it is the top compression ring which gives the most trouble, though there are examples to the contrary, *i.e.*, where the third compression ring is the most troublesome and sticking travels up the piston, rather than from the top ring downwards. The incidence of ring-sticking varies between different types of engines, and has everywhere been reduced, though not eliminated, following upon the adoption of detergent type oil.

Some of the vehicles operated by the Road Haulage Executive are engaged on " in town " delivery work, where conditions are more akin to those of bus operation than to long-distance haulage. Engines from this type of service, when stripped for overhaul, have been observed to be in a condition but little different from that of London bus engines, ring-sticking or excessive carbon deposits being mainly confined to the top scraper. The only point of difference worthy of mention is that engines from these short distance delivery vehicles exhibit more evidence of sludging than is normally found in bus engines after a comparable period in service.

The foregoing information, representing as it does the opinions of operators of many thousands of C.I. engined vehicles, leads to the following generalized conclusions :—

(1) that the incidence of ring-sticking varies with both engine make and type of service operated ;

(2) that certain provincial bus operators are experiencing no troubles and are obtaining complete satisfaction from the use of non-detergent type oil ;

(3) that where ring-sticking has been encountered, the trouble has been reduced, though not eliminated, by the adoption of detergent type oil ;

(4) that with engines performing long-distance haulage duties—in either goods or passenger service—it is the compression rings which are the first to stick ; in the majority of cases ring-sticking travels from the top ring downwards ;

(5) that with engines in bus service, both London and provincial, it is the top scraper ring which gives the most trouble, though stuck compression rings are not unknown.

From the viewpoint of this symposium, conclusions (4) and (5) are the most important, for they show that whereas the Caterpillar L.1 test might be claimed to be of some value in the selection of detergent type oils for use in engines engaged in long-distance haulage, it has little or no application to the selection of oils for use in bus engines. It could be argued from this that an alternative test ought to be developed to rate oils intended for use in bus engines ; whether this test should involve the use of a new test engine or whether it would be preferable to retain the Caterpillar engine and merely to develop an alternative test procedure is a matter which might be debated though it is probable that the oil suppliers would favour the retention of the Caterpillar engine.

Assuming that two alternative tests or test procedures were established,

it might well be that the oil industry would find it necessary to market two grades of detergent type oil, one for engines in long-distance haulage vehicles, the other for buses. It may be questioned whether such a course would be favoured by operators. For example, a passenger transport concern is likely to operate both buses and coaches, and in the provinces and in London Transport's country area also there are many occasions upon which buses operate as coaches and vice versa. Similarly, an operator of goods vehicles may run long- and short-distance haulage services from the same depot; it is sometimes the practice for one and the same vehicle to perform long-distance haulage duties by night and to be engaged in " in town " delivery work on the succeeding day. Operators might therefore find difficulty in deciding which of the two grades of detergent oil they ought to adopt, and would tend to ask for guidance as to which was the more all-round suited to their requirements. The answer to this difficulty is surely that, apart from high additive oils advocated for special purposes, the oil industry ought to market a grade of detergent type oil which would be suitable for use by any C.I. engined road vehicle irrespective of its duty. Such an oil would not be satisfactorily rated by the Caterpillar L.1 test, and a new test or test procedure is therefore required.

In developing this new test an effort should be made to dispense with the use of the Caterpillar engine, which owing to its high installation and running costs, is of very restricted application. There is pressing need for a less expensive and less time-consuming test method which could be employed by large users of detergent oils and which would not be without interest to the oil industry, where small engines are in constant use for assessing the performance of lubricating oils. The onus of developing an engine test for rating oils suitable for use in goods and passenger vehicles alike rests clearly with the oil industry, which at the present time is marketing detergent oils designedly suitable only for engines engaged in long distance work—if indeed Caterpillar L.1 ratings are to be relied upon at all in relation to the requirements of British engines. For it must not be forgotten that the adoption of detergent type oils by operators in Britain has been based, not upon the engine tests called for in the U.S. Ordnance Board and British Ministry of Supply specifications, but upon service experience. Such experience is of necessity restricted and, in the case of London Transport and of operators who are making use of London Transport's specification, is confined to a particular type of base oil. This specification, which as already mentioned demands that the base oil should be blended with the appropriate proportion of an approved detergent additive, is, of course, open to criticism, but it is contended that it is more truly indicative of user requirements than either the MIL or DEF specifications, which are in essence based upon the Caterpillar L.1 test.

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APPENDIX I

CHARACTERISTICS OF BASE OILS CALLED FOR IN LONDON TRANSPORT'S SPECIFICATIONS FOR DETERGENT-TYPE OILS OF SAE 20W AND SAE 30 VISCOSITIES

	(*a*)	(*b*)
SAE No.	30	20W
" London Transport " type	U.113	U.118
Sp. gr. at 60° F	Not specified	Not specified
Kin visc :		
At 140° F, cs	39·0–42·5	22·0–26·5
At 210° F, cs	11·0 min	7·8 min
Redwood visc at 140° F, sec	160–175	95–110
Viscosity Index	90 min	90 min
Pour point, ° F	15 max	0 max
Closed flash point, ° F	400 min	400 min
Carbon residue (IP14/45), %	0·5 max	0·3 max
Oxidation characteristics (IP 48/44) :		
Viscosity ratio (at 140° F)	1·5 max	1·5 max
Carbon residue increase, %	0·7 max	0·6 max
Asphaltenes after oxidation, %	0·05 max	0·05 max

MILITARY REQUIREMENTS FOR LUBRICATING OILS FOR COMPRESSION-IGNITION ENGINES

By D. I. BADDELEY (Associate Fellow), MAJOR R. W. EGGLESTON, R. W. LONG, and A. WATSON (Associate Fellow)

THE CONDITIONS

IT would appear obvious that any military equipment will generally have a more strenuous and difficult life than its civilian counterpart. Although some of the supposedly severe conditions of service are either non-existent or infrequent, the operating conditions associated with military use which do impose unusual strains on equipment in the field may be listed as follows, not necessarily in order of importance :—

(*a*) regular operating schedules are not always possible, and the proportion of time spent idling may be comparatively high;

(*b*) emergency starting, overdriving, overloading, irregular service and maintenance must be accepted as inevitable under active service conditions;

(*c*) the risk of contamination during handling of fuels, lubricants, etc., with dirt and water (fresh and salt) is generally higher;

(*d*) storage of equipment under indifferent conditions for periods of more than twelve months without replacement of used oils may occur;

(*e*) considerations of supply in the field require the strictest limitation in the number of grades of lubricants for any one functional purpose;

(*f*) equipment will be expected to operate, with minimum modification, in ambient air temperatures over the range of −65° F to 125° F;

(*g*) stocks of fuels, lubricant, and allied products may be held in storage for relatively long periods before use;

(*h*) vehicle engines will be expected to operate with a heavier load factor due to the proportion of cross-country running.

All the above conditions are dealt with to a greater or lesser degree by suitable design of military equipment, but two further factors exist outside the scope of military design. The first is that, in war, and to some extent in peace, much equipment of completely or basically commercial design is used for military purposes. The second is that considerations of international co-operation require that fuels, lubricants, and allied products shall, so far as possible, be suitable for use in similar roles in the equipment of allied land forces. When the cumulative effect of these conditions is examined it is realized how they conflict and so multiply the obstacles which face the designers of equipment and those who write the specifications for the fuels, lubricants, and allied products which are required for such equipment.

The Requirements

Having noted the above conditions, it is possible to list the qualities required in the case of a crankcase oil for compression-ignition engines while recognizing that some of the requirements are, in practice at any rate, in conflict and that any material actually obtained must be a compromise. Nevertheless, it is necessary to appreciate these requirements, since it is highly desirable to be able to assess the degree to which any single requirement is fulfilled by any specification or physical sample. These requirements, many of which are also well known in civilian practice, may be stated as follows :—

1. *Film Strength*

The oil should provide a thin, strongly adherent film which will give the minimum friction coefficient and eliminate, as far as possible, metal to metal contact between working parts.

2. *Blow-by*

The oil film should, as far as possible, seal the combustion gases within the cylinder and resist blow-by.

3. *Heat Transfer Properties*

The oil should act as an efficient cooling medium, carrying heat rapidly away from locations of high temperature.

4. *Protection of Metal Parts*

The oil should protect metal parts of the engine from corrosion and not be unduly detrimental to the accepted types of seal.

5. *Resistance to Oxidation in Service*

The oil should show satisfactory resistance to oxidation under the conditions of engine operation.

6. *Detergency*

The oil should act as a detergent, keeping the engine interior free from the deposition and build-up of sludge, carbon, and other contaminants.

7. *Compatibility*

The oil obtained to one specification should be compatible, in respect of base oils and additives, with all other oils supplied to that specification.

8. *Balance between Quality and Availability*

A reasonable balance should be maintained between desirable quality and quantity availability.

9. *Suitability for S.I. Engines*

An oil used for compression-ignition engines should be suitable for spark-ignition engines in military use. In particular, any deposits formed in the cylinder head and arising from the use of additives shall not aggravate pre-ignition.

10. *Long Term Storage*

The oil should be capable of long term storage in the unused state and relatively short term storage in the used state without forming compounds harmful to engines.

11. *Suitability for Commercial Type Engines*

The oil should not be fundamentally unsuitable for use in the common types of commercial engine.

12. *Sensitivity to Contamination*

The oil should be less sensitive to contamination with dirt and water (fresh and salt) than commercial oils of similar type.

13. *Temperature Range of Satisfactory Operation*

The oil should give satisfactory performance in service over the widest possible ambient air temperature range.

14. *Pourability*

The oil must be pourable from its container at the minimum specified ambient air temperature.

15. *Foaming*

The oil should show the minimum foaming tendency.

The Existing Methods of Assessment

In existing specifications for oils of this type, the following tests are made to establish the quality of the materials supplied: flash point; viscosity at 0°, 100°, and/or 210° F as appropriate; viscosity index;

pour point; foaming test; ring sticking and wear test by CRC L.1 procedure on the Caterpillar engine; oxidation and corrosion test by CRC L.4 procedure on the Chevrolet engine; compatibility test.

The purpose of, and information to be derived from, the above may be summarized as follows :—

Flash Point

Required for safety purposes under both storage and running conditions.

Viscosity

Indicates (i) the degree of viscous drag which will oppose starting, (ii) oil distribution and flow at all operating temperatures, (iii) the ability of the film to resist breakdown under load at operating temperatures. It deals partially therefore with requirements 1 and 2.

Viscosity Index

Gives an indication of the variance of viscosity with temperature. It helps to establish the degree of achievement of requirements 1 and 2; it also gives some measure of answer to requirement 13.

Pour Point

Measures the ability of the oil to flow from its container, and in a measure of compliance with requirement 14.

Foaming Test

Gives an indication of the ability of the oil to reject entrained air. This measures the compliance with requirement 15.

CRC L.1 Test on the Caterpillar Engine *

This test at normal operating temperatures gives information as to ring sticking, deposition of carbon and sludge, wear on piston lands, skirt and rings and cylinder bore, heat dissipation rate, lubricating oil consumption, average rate of piston blow by. Partial answers are thus given to requirements 1, 2, 3, 6, and 11.

CRC L.4 Test on the Chevrolet Engine *

Indicates the resistance of the oil, under the conditions of high speed, high temperature gasoline engine operation to : (i) oxidation; (ii) formation of corrosive products; (iii) sludge deposition.

It also gives a slight measure of the oil's heat transfer properties. Partial answers are therefore given to requirements 4, 5, 6, 9, and 11.

Compatibility

Since compatibility cannot physically be established with every other approved oil, this determination can only be a partial fulfilment of requirement 7.

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* The results of these tests must be regarded as coming from pieces of test apparatus rather than from working engines.

The Adequacy of Existing Tests

It is now possible to summarize the extent to which existing tests ensure that the requirements are met.

1. *Film Strength*

The wear disclosed by CRC L.1 Test, the viscosity, and the viscosity index give a reasonable picture of film strength, lowering of friction, co-efficient and prevention of metal to metal contact over a narrow range of engine temperature conditions. Information is lacking as to the effects on film strength of changes in r.p.m. and load.

2. *Blow-by*

In the CRC L.1 test, blow-by is measured by the effect on engine parts is not assessed, while the reverse is true in the L.4 tests.

3. *Heat Transfer Properties*

The present methods of test give little information on heat transfer properties of the oil.

4. *Protection of Metal Parts*

The protective quality of the oil during the test period in an S.I. engine is moderately well dealt with.

5. *Resistance to Oxidation in Service*

This aspect of oil quality appears to be adequately covered in the S.I. engine tests but only to a limited extent under C.I. engine test conditions.

6. *Detergency*

This requirement should be capable of complete assessment by existing test methods provided that test fuel quality and oil drain periods are representative of current supply and procedure.

7. *Compatibility*

The present test of compatibility can best be described as inadequate.

8. *Balance between Quality and Availability*

This desirable state of affairs is, at present, fairly satisfactorily achieved by the close co-operation between the users and the suppliers. Such co-operation includes forecasts of availabilities in war, and encouragement for the production of additives of all types in U.K.

9. *Suitability for S.I. Engines*

The existing L.4 test will reveal adverse effects of high temperature on the oil, although it must be realized that the concurrent high pressures encountered at full throttle in service do not occur in the test. Any tendency for additives or additive decomposition products to cause pre-ignition will be revealed.

10. *Long-term Storage*

Present specification tests provide no information at all on this subject.

11. *Suitability for Commercial Type Engines*

This can only be assured by close co-operation between engine manufacturers and oil companies.

12. *Sensitivity to Contamination*

This requirement is not covered by any existing tests.

13. *Temperature Range of Satisfactory Operation*

Of all the qualities required of the oil, the effect of temperature variation is only indicated to any degree in the case of viscosity. Performance data are fairly adequate at normal and high temperature, but low temperature, starting, and warming up conditions are not covered.

14. *Pourability*

This is satisfactorily taken care of by the pour point test.

The Additional Information Required

For ease of reference the additional information will be listed under the headings already used in the preceding paragraphs, and the additional information required is as follows :—

1. *Film Properties*

Information is needed on reduction of wear under varying load and speed conditions, with particular reference to the effects of the condition of boundary lubrication believed to occur during long periods of idling.

2. *Blow-by*

Additional information is required to correlate the blow-by observed in test engines with crankcase corrosion and sludge deposition under all conditions.

3. *Heat Transfer*

Measurements should be made of the variation of this property with composition and prolonged use.

4. *Protection of Metal Parts*

Some data on the protective quality of the oil in C.I. engines under varying atmospheric conditions is essential.

5. *Resistance to Oxidation in Service*

Additional information on the behaviour of the oil under conditions of high temperature in a C.I. engine is required.

6. *Detergency*

No additional information appears necessary at present.

7. *Compatibility*

There is a need for some method of assessment of compatibility in service.

8. *Balance between Quality and Availability*

This is not resolvable by methods of test.

9. *Suitability for Use in S.I. Engines*

Information is needed on oil behaviour under conditions of varying load and speed, including the conditions of prolonged idling.

10. *Long-term Storage*

Information is required on ageing of oils.

11. *Suitability for Commercial Type Engines*

Information is required to ensure that commercial engines, for which oils not in Army supply are specified, can readily be made to operate satisfactorily on Service grades.

12. *Sensitivity to Contamination*

Data are required on the reactions of additives to water and salt.

13. *Temperature Range of Operation*

Information on operating efficiency under low temperature and warming up conditions is a requisite.

14. *Pourability*

No additional information is required.

The Suggestions

The primary suggestion which the authors seek to make is one which, though relevant to the field at present under consideration, has a much wider application.

It is a plea for co-ordinated and co-operative research to establish the qualitative and quantitative significance of the readily measurable chemical and physical properties of lubricants in terms of operational engine performance, particularly in regard to their effect on output and reliability.

Performance testing is a confession of failure on the part of the engine designers, builders, and users, as well as the lubricant providers. It is an admission that the theory of lubrication and the relative importance of the lubricants' chemical and physical properties are still mysteries. Moreover, a generally accepted performance test, by the time it reaches some degree of international standardization, is no longer representative of general user practice. Such a performance test has, by that time, become merely a highly complex routine, capable of assessing certain limited qualities of oils under narrowly limited conditions with an expensive piece of somewhat unrepresentative test apparatus.

It is fully appreciated that the type of research referred to above is long term, costly, and difficult to control. The great need is for the setting up of some very small body similar to the American CRC representing manufacturers, designers, and users of I.C. engines and similar equipment, together with fuel and lubricant producers. Such a body should, through its associations, be able to call on the services of virtually the whole resources in the U.K. within this field.

Research of the type outlined above is long term, and the short term objective must be to suggest methods of simplifying, shortening, and

cheapening existing test methods and/or obtaining further usable data from them. These are described in general terms as follows :—

(*a*) The replacement of the existing CRC L.1 test by a shorter C.I. engine test, including cycling periods on an idling, full speed, maximum torque routine, periods of cold starting, and determination of full throttle curves. This will take care of additional information requirements 1 and 13 above. Modifications of instrumentation and examination should be made to provide the basis for other suggestions below.

(*b*) The development of techniques or methods of assessment of data determinable in (*a*) for the evaluation of bearing corrosion, cylinder wear, sludge formation, and resistance to oxidation. These will provide answers to additional information requirements 2, 4, and 5 above. In commenting upon technique and assessment of data the authors wish to point out that they feel that the existing test methods yield data which, with careful investigation and correlation, could contribute to the solution of these requirements.

(*c*) Development of a brief simple spark-ignition engine test involving cycling, cold start, and prolonged idling and conditions of gasoline dilution to assess bearing corrosion pre-ignition promotion and sludge formation. This covers additional information requirement 9.

(*d*) Development of accelerated physical tests to indicate storage stability of additive type engine oils under both hot and temperate conditions with and without fresh and salt water being present. This will cover additional information requirements 10 and 12.

Acknowledgments

The authors desire to express their thanks to the War Office and Ministry of Supply for permission to publish this paper.

NOTES ON HEAVY DUTY OILS—SOME EXPERIENCES OF A DIESEL ENGINE MANUFACTURER

By D. M. Pearce *

Introduction

Results of tests carried out by a firm of diesel engine builders to establish what oils are best suited to their engines are outlined in this paper. The approach has been subjective, and it cannot be claimed that the results are generally applicable. It is one of many widely differing aspects of research and development work which the company conduct on a scale that is small in comparison with the resources available to several laboratories in the U.K. devoted solely to the testing of engine lubricants. Moreover, the writer and others concerned with this work are by no means expert

* Messrs Davey, Paxman & Co. Ltd.

on lubricating oils; preoccupied with the engines themselves, they tend to pay insufficient attention to such matters. Nevertheless, the writer believes that some of the information may be of interest to those more actively concerned with lubricating oils, since the engine builder gives guidance to the user in the light of his own inexperience.

Reasons Leading to the Adoption of H.D. Oils

About five years ago, reports of ring sticking on engines in service after comparatively short periods of running were received in increasing numbers. At first they applied to one engine type in particular, but later other types were similarly affected, but to a lesser extent. The engine type first to suffer was one that had been in production for about ten years and had previously a fairly good record, not normally being considered as a "ring sticker." The situation rapidly became worse, and it was soon clear that the reasons could not be attributed solely to such factors as (*a*) more severe operating conditions, (*b*) the greater number of engines in service, or (*c*) the more exacting standards demanded owing to progress made in increasing the reliability of engines generally. The design had not been changed, and there was no evidence that the quality of manufacture had deteriorated. Such possible causes, however, were discounted by the fact that engines that had not previously given trouble and which were operating under the same conditions as before succumbed to ring sticking.

There appeared to be no simple explanation, and attention was drawn to the fact that the sulphur content of the fuels generally available appeared to have increased. Hitherto little importance had been attached to the sulphur content or, in fact, to other properties of the fuel, it being considered sufficient to specify simply a Class A fuel. Reports from oil companies tended to be inconsistent and conflicting, both as to whether and by how much the sulphur content in the fuels generally available had risen over the last few years and if an increase in the sulphur content would be likely to lead to this state of affairs. However, the published results of tests carried out by Caterpillar and others in the U.S.A., coupled with the fact that no other reason could be found, pointed more and more to the belief that the increased sulphur content might be the most important single contributory factor to the very marked increase in ring sticking tendencies of these engines. Tests carried out with a special low sulphur fuel added weight to this belief.

A series of tests mainly of relatively short duration were carried out to find the causes, and to effect a cure. At first only gas oil that was currently available and the straight mineral oil normally recommended were used. Alterations were made that effected combustion, operating temperatures, and piston ring layout; but conditions were either unchanged or worsened. An exception was piston cooling; oil-cooled pistons gave promising results on short tests. But it was not practical to introduce piston cooling on an engine that had not only been in service for a number of years but which was scheduled to go out of production before long. Finally, but not very hopefully, detergent oils were tried. (On one or two previous occasions certain of the power house engines had been run on detergent oils, but since they had not been prone to ring sticking when using

a straight mineral oil, the advantages of a detergent oil were not fully appreciated at the time. It is also possible that the detergent oils tried were not particularly good ones.) In this case, however, results were most encouraging. A very marked improvement in engine cleanliness and freedom from ring sticking was observed with a detergent oil and, after further endurance running on two different makes of oil, detergent oil was recommended for this particular type of engine and approval given to the two oils which had been tested. The results in service were very satisfactory, and complaints about ring sticking were almost entirely confined to users who had not changed to a detergent oil. The length of period between overhauls was increased by two or three times the previous figure.

Establishing Procedure for Testing Suitability of H.D. Oils

At this time little was known of the significance of the Caterpillar tests for H.D. oils which were becoming accepted in the U.S.A. or as to how individual engine types would respond to H.D. oil treatment. It was therefore decided that a particular make or type of H.D. oil should be approved only after a test had been run and satisfactory results obtained. Short tests (50 to 100 hr duration) under extreme conditions of load and temperature were tried, but it was difficult to translate results into those that would have been obtained after fairly long periods of running in service; and rather than embark on a long term investigation to correlate these accelerated tests with service conditions, it was decided to run long duration tests on the power house engines which corresponded at least to a certain type of service condition. At first any engine that was available in the power house was used, but after obtaining a number of inconclusive and unrelated results all oil tests were run on one engine type only, namely the engine which had first given so much trouble in service and which was the worst engine in the range as regards ring sticking.

The testing of H.D. oils has now become a matter of routine. Four engines in the power house, apart from generating useful power, are used also for approval testing of H.D. oils. Operating conditions are very similar on all engines, and the load can be controlled to within 60 to 85 per cent of full load for most of the running period. Oil and water temperatures are controlled to within about 15° F. The duration of each test is 1000 hr. New rings and sometimes pistons and liners are fitted, and the engine is thoroughly cleaned before each test. The oil is changed after 500 hours and samples taken every 100 hours for analysis; the sump is topped up every day in order to keep the dilution of new oil to a minimum. A new oil filter element is fitted before each test and cleaned after 500 hours. The fuel is Pool gas oil, and although samples are analysed periodically no attempt is made to allow for the variations which occur. The engine is stripped for examination at the end of the 1000-hour run. By this means it is possible to test about six oils in the course of a year.

Test Results—Correlation with Standard Tests

The standard by which an oil is considered acceptable is based on results obtained when using the oil first approved and which is known from considerable service experience to give acceptable results. This is the

reference oil, and is periodically used in one or other of the test engines to check whether conditions remain constant. It is simply a pass or fail test; no attempt is made to assess a numerical rating; if the engine condition is judged to be approximately as good or better than after running on the reference oil it passes the test; if it is appreciably worse it fails.

The condition of the engine is assessed mainly on piston cleanliness—scraper ring plugging, carbon build up, and lacquer formed in ring grooves and skirt—on general deposits on the crankcase, cylinder heads, etc., and on lacquer deposits on the liners and small end bushes. Liners, pistons, and rings are checked for abnormal rates of wear.

The few check runs that have been carried out on the reference oil indicate that operating conditions are fairly consistent. However, they are clearly not controlled laboratory tests nor were they intended to be, and truly repeatable results cannot be expected for the following reasons :—

(*a*) the operating conditions—loading and temperature cannot be controlled accurately, and vary from test to test;

(*b*) for economy the engines are not rebuilt as new before each test, and even when new liners and pistons are fitted the normal manufacturing tolerances are accepted;

(*c*) the properties of the fuel vary;

(*d*) the engines are maintained by the power house personnel, who are not skilled engine testers.

Nevertheless, it is believed that these tests enable oils unsuited to the duties normally performed by these engines to be rejected, since the test conditions are typical of many in service.

Most of the oils submitted for test are claimed by the manufacturers to meet one of the American specifications, 2-104B, MIL-0-2104, or 2-104B Supplement I, the choice of oil submitted being left to the oil company concerned. This has enabled the performance of a number of oils to these three specifications to be observed. In general, oils to these specifications can be distinguished as falling into two main groups on the basis of the test results. The first group, generally oils claiming 2-104B, give results that are poor or fair, and the second group, generally oils claiming MIL-0-2104 or Supplement I give results that are good or very good. However, this very approximate correlation between these test results and the standard specifications is not invariably observed. One oil claiming Supplement I gave results that were barely good enough for the second group, and an oil claiming only MIL-0-2104 gave as good or better results than only oil claiming Supplement I. Probable reasons for such inconsistency are :—

(*a*) variations in the operating conditions of the tests;

(*b*) variation in the standards required for passing the American tests;

(*c*) some oils are claimed by the manufacturers to be of "Supplement I or 2-104B type," no claims being made that the particular blends tested have been submitted to the actual tests. This may be a somewhat arbitrary standard;

FIG 1

CONDITION OF PISTON AFTER 1000-HOUR TEST ON POOL GAS OIL USING A H.D. OIL TO MIL-O-2104 SPECIFICATION, SAMPLE A

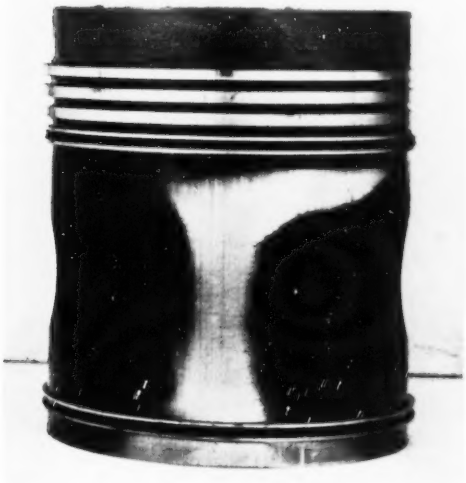

FIG 2

CONDITION OF PISTON AFTER 1000 HOUR TEST ON POOL GAS OIL USING A H.D. OIL TO MIL-O-2104 SPECIFICATION, SAMPLE B

[To face p. 556.

FIG 3

CONDITION OF PISTON AFTER 1000-HOUR TEST ON MARINE DIESEL FUEL USING A H.D. OIL OF 2-104B SUPPLEMENT TYPE

FIG 4

CONDITION OF PISTON AFTER 1000-HOUR TEST ON MARINE DIESEL FUEL USING A H.D. OIL OF 2-104B SUPPLEMENT II TYPE

(*d*) an oil that easily satisfies the MIL test might satisfy the Supplement I test if it were submitted; such an oil might be compared with another that had only just satisfied the MIL test;

(*e*) the performance of an oil may show up differently in different types of engines.

Figs 1 and 2 show photographs of pistons after testing two oils, both claiming MIL-0-2104 standard.

At the time of writing, seventeen oils have been tested and only three rejected. Of the oils rejected, two were claimed to meet 2-104B specification only, and no standard specification was claimed for the third. Of the oils passed, six claimed Supplement I, two MIL, and the remaining six 2-104B, some companies claiming only "——— type." Most of the six oils last referred to were tested and approved during the early stages in attempts to standardize on a test procedure, and it is more than likely that some of these oils if tested again would not reach the level of performance now considered necessary.

It is now considered that approval could safely be given to the use of any oil meeting 2-104B Supplement I specification, and although there is little doubt that this could also apply to all oils meeting MIL-0-2104, rather more experience is desirable with oils to the latter specification.

H.D. Oils and Special Operating Conditions

Class B Fuel

In view of the tendency for high-speed diesel fuels to be less readily available and more expensive throughout the world, the behaviour of engines on lower grades of fuel is becoming of greater interest. So far tests have been confined to diesel fuels coming within the limits set by BS Class B but outside Class A, and considerable experience has been gained on engines in the power house running on such fuels. The commercial grade of marine diesel fuel which has been used is not as bad in all respects as a Class B fuel could be, but it is representative of fuels normally used in large marine diesel engines. A typical analysis is given in Table I, together with a typical analysis of the Class A gas oil.

Table I

	Approximate specification of gas oil	Typical analysis of marine diesel fuel
Sp. gr. at 60° F	*ca* 0·84	0·874
Viscosity, Redwood I at 100° F, sec	34	38
Flash point (closed), ° F	150 min	—
Pour point, ° F	20 max	—
Distillation recovery at 350° C, %	90 min	—
Carbon residue, Conradson, %	0·05 max	1·07
Sulphur content, %	0·8 to 1	1·27
Diesel index	48 min	44
Sediment content, %	—	0·05
Water content, %	—	0·05
Ash content, %	—	Less than 0·01

Most of this work has been carried out on a larger engine than the type previously referred to, although the nature and duration of the tests have been similar. An H.D. oil is normally used in these engines when using a Class A gas oil, and it is found that whilst the piston deposits are much the same after about 1000 hours running on both fuels, the deposits on the valves and in the ports are somewhat heavier when using marine diesel fuel. The only serious harmful effect of the heavier fuel that has been observed is the increase in side wear of the top piston ring groove. Comparative runs were made using Supplement I and Supplement II type oils, and it was found that the top ring groove wear and the valve and port deposits were about the same with the two oils. The pistons, which were reasonably clean after test with a Supplement I type oil, were exceptionally clean with Supplement II type oil, and comparative photographs are shown on Figs 3 and 4. Although no comparative tests were made with a straight mineral oil, it appears that the rate of top ring groove wear is little influenced by the type of oil used.

Corrosion of Small End Bushes

On one engine type, particularly when operating conditions are conducive to high piston temperatures, heavy lacquering and corrosion of the phosphor bronze small end bush occurs with certain types of H.D. oil. It is understood that this is due to certain oil additives attacking the phosphorus in the bush, above a certain temperature. Measurements taken by means of fusible plugs showed that under normal operating conditions at full load the mean temperature of the small end bush is about 150° C, with a maximum temperature somewhere below 180° C. This is somewhat lower than has been quoted as the threshold temperature for this type of corrosion, but the method of measurement is not very precise, and higher operating temperatures may occur in practice.

This form of corrosion has not been observed on the engine type used for H.D. oil approval tests, and thus the behaviour of the oil in this respect escapes notice. Special laboratory and engine tests were contemplated with a view to establishing whether an oil brought about such corrosion, but were ruled out on the score of the complications involved and the difficulties of obtaining consistent results. The oil companies concerned tended to be somewhat evasive on the subject of their own oils. A material containing no phosphorus (silicon bronze) was tried, and results were very satisfactory and no signs of corrosion and only traces of lacquer appeared under conditions where severe corrosion and heavy lacquer deposits occurred with the phosphor bronze bushes. This material has now been standardized for small end bushes on all engines, and no reports of this trouble have been received from engines in service fitted with the new bushes.

SOME EXPERIENCES WITH A SHORT DURATION LUBRICATING OIL TEST ON A MULTI-CYLINDER COMPRESSION-IGNITION ENGINE AND ASSOCIATED SERVICE TESTING

By A. Fogg * and G. R. Oliver *

Summary

This paper describes experiments carried out at the request of a number of British road vehicle compression-ignition engine manufacturers with the object of developing a relatively simple and short duration engine test method for assessing, on a broad basis, the suitability of lubricating oils for such engines.

Work in the laboratory on a typical multi-cylinder compression-ignition engine widely used in British vehicles is described in detail, and results of tests with a number of plain and additive-type lubricating oils are given and discussed. Various criteria for assessing performance are proposed. Results of extensive service tests on the same oils, carried out by two of the largest operators of public service vehicles in the U.K., are also given and compared with the laboratory results.

Although the results obtained in 50-hour tests in the laboratory are in broad agreement with Caterpillar L.1 tests on the same oils, correlation with P.S.V. service is unsatisfactory. Possible reasons for this lack of agreement are discussed.

Introduction

For many years the development of additive-type crankcase oils has been based on the familiar L.1 and L.4 American test procedures. Whilst these procedures have no doubt been useful in raising the general level of lubricant performance (since they have constituted a fixed performance standard over a number of years), they appear to have been applied rather indiscriminately over a wide range of engine types and service conditions without adequate experimental backing in the form of data establishing correlation between the tests and service operation. This lack of correlation data is even more important in the U.K. than in America because of the extent by which British service conditions and engine design practice differ from those of America. The extreme precision with which these tests are applied to service also requires much more correlation data than has been published to sustain it. For these reasons, and also because of the difficulty and expense of obtaining the required American test engines and spare parts, these tests have never been popular with U.K. engine makers and operators.

Against this background the Motor Industry Research Association was requested, by several of its member firms, to examine the possibility of establishing a simple and inexpensive test procedure for selecting beneficial lubricating oils for British road vehicle compression-ignition engines. Such a procedure would enable manufacturers and users to test and select lubricants and not have to specify proprietary brands.

* Motor Industry Research Association.

In the state of present knowledge, it is generally accepted that any such test procedure must consist essentially of an engine test, since no simpler means has yet been devised or, in fact, appears possible, of combining and controlling the various factors which exert an influence. From discussions among representatives of engine manufacturers and vehicle operators it was generally agreed that such a test should :—

(*a*) in view of British experience, be concerned primarily with piston ring behaviour;

(*b*) discriminate between oils on a " go " or " not-go " basis and not differentiate on a close merit basis;

(*c*) preferably be of short duration; and

(*d*) in the first place, make use of a typical British multi-cylinder engine, in order to embrace, to the maximum extent, the various detail design features which may have a bearing on the problem.

Any test procedure which might be developed must, obviously, correlate satisfactorily with road operation, and in the absence of data on the relative merits of H.D. and plain oils in British road vehicle compression-ignition engines, it was agreed that service tests on as large a scale as possible should be organized. Accordingly, the co-operation of two of the largest operators of public service vehicles (compression-ignition engines) in the U.K. was obtained to carry out service tests on the same oils to be used in the laboratory work.

Representatives of member oil companies, acting through the Institute of Petroleum, kindly arranged to select the oils and additives, as referred to later, and to ensure that the oils supplied for both laboratory and service tests were identical. Further, the same representatives arranged for CRC L.1 laboratory tests be carried out on the same series of oils in their own laboratories.

Laboratory Tests

Description of Engine and Experimental Set-up

Engine. For the laboratory tests a six-cylinder, 10-litre, direct injection, compression-ignition engine was used which had a bore of 4·8 inches, a stroke of 5·5 inches, and a compression ratio of 15·75 : 1. Its rated maximum output was 125 b.h.p. at 1800 r.p.m.

Constructional details included an integral cylinder block and crankcase, and a hardened crankshaft running in seven bearings. Both main and big-end bearings were pre-finished copper–lead, thin shell type, with indium coatings. Bronze bushes were used for the small ends, and slip fit, quenched and tempered cast iron cylinder liners tin plated internally and externally were fitted. The pistons were tin-plated aluminium alloy, and carried three, hardened and lapped, cast iron compression rings, and one slotted scraper ring above the gudgeon pin. Modifications made to the pistons for test purposes will be described under Test Procedure. Two detachable cylinder heads incorporated stellited valve seat inserts, the valves having stellited faces and hard chromium plated stems.

The fuel injection equipment was standard, the engine not being derated. A combined mechanical and vacuum governor controlled the maximum and intermediate speeds of the engine, the former being 1900 r.p.m.

The fuel injection pump was set to give a delivery of 84 cu. mm. per stroke with a maximum variation of 2 per cent between cylinders. Four-hole injectors were fitted, and the injection pressure was maintained at 150 to 160 atm.

Lubrication and Cooling Systems. Since close control of running temperatures would obviously be important in the development of an engine test, the lubrication and cooling systems were modified with this in view before testing was commenced.

Lubrication of the standard engine was on the wet sump principle, circulation being by a gear pump to the bearings and rocker gear, and by splash to the gudgeon pins. The cylinder walls and the cams received an intermittent spray from oil jets drilled in the connecting rod big-ends. The oil filter was of the full-flow, cloth element type, and sludge traps were incorporated in the hollow crank journals. The sump capacity was 6 gal. This system was modified to include an oil cooler, which was fitted between the gear pump in the sump and the relief valve, to ensure that all the oil passed through the cooler. This necessitated moving the relief valve to a separate mounting on the test bed. In addition eight 250-watt infra-red heater lamps were mounted under the sump. A double circuit electrical temperature controller operated both the heater under the sump and a magnetic relay valve controlling the flow of cooling water to the oil cooler. This arrangement enabled the oil temperature to be controlled to within $\pm 1^\circ$ C, and was also useful in reducing warming-up time on starting from cold.

The cooling system was modified by removing the thermostat and plugging the by-pass passage. A closed circuit was employed for the coolant, and sodium benzoate was added to the coolant to inhibit scale formation and prevent variations in heat transfer. Heat was extracted from the coolant in a heat exchanger, and close control of the coolant outlet temperature was obtained by means of an electrical temperature controller operating a magnetic relay valve which diverted the coolant through a pipe by-passing the heat exchanger. This system enabled the temperature to be maintained constant within $\pm 1^\circ$ C. To enable the engine to be run at high jacket temperatures a 50/50 solution of ethylene glycol in water was used as the coolant.

Auxiliary Equipment. The engine was coupled by a propeller shaft and flexible couplings to an absorption dynamometer from which the engine torque was determined. Fuel consumption was measured by timing the flow from a fuel bulb. This included the fuel leak off from the injectors, but as this quantity was found to be less than 0·5 per cent of the total no correction was made.

Oil pressures were measured at the oil gallery and at the inlet to the filter. Fouling of the oil filter was indicated by an increase in the difference between these pressures.

A sensitive gas meter connected to the crankcase vent was used to measure the blow-by. No special arrangements were made for sealing the crankcase, as the normal oil seals in the engine were found to be effective at the low back pressure offered by the gas meter.

A smoke density meter was used to measure the exhaust smoke. It consisted of a long cylinder, through which a proportion of the exhaust

gases were passed, with a photo-electric cell at one end and a light at the other. The fall in the intensity of the light reaching the cell, when exhaust gas was passing through the cylinder, below the intensity with clean air, was taken as a measure of smoke density. These readings of exhaust smoke density were taken to indicate any appreciable change in combustion conditions during the course of the test.

Lubricants and Fuels

The selection of test oils for use in the laboratory and by the two bus companies was made independently of MIRA by representatives of co-operating companies. Each bus company carried out tests only on the plain oil currently used by it and on additive oils based on that plain oil. Three proprietary detergent additives were also selected by the co-operating oil companies, and blended with the two base oils. The names of these additives were withheld from MIRA until the tests had been completed. Thus, the test oils consisted of two plain good quality oils which have given satisfactory service and oils blended with additives representative of those on the market in 1948, and claimed to be beneficial in service. The two operators and the base oils they tested will be referred to as "A" and "B," the additives as "1," "2," and "3," and the additive oils as "A1," "A2," etc., throughout this paper.

Two fuels were used for the laboratory tests, one of low- and the other of high-sulphur content. Both fuels were IP Reference Gas Oils, the former containing 0·2 per cent sulphur, and the latter 1·0 per cent sulphur. In each case the fuel was drawn from a single batch laid down for testing purposes. The service tests were conducted on the supplies of fuel commercially available at the time. Some remarks on the variation of sulphur content of these fuels will be found in the description of the service tests.

Test Procedure

Obviously, some departure from normal practice of fitting and running would be required to give a test of reasonable duration. The most apparent way of accelerating ring sticking is by increasing the temperatures in the region of the ring belt, but there appears to be a strong case for limiting this increase so that the temperatures do not appreciably exceed those encountered under the most severe service conditions; otherwise the chemical reactions which take place may not be representative of those occurring in service and, particularly in the case of additive oils, the results may be misleading. Other means of accelerating a test were therefore considered. Since wedge-shaped compression rings, as normally fitted to this engine, were likely to be unsuitable for an accelerated ring-sticking test, the pistons used for the test were designed to carry parallel-sided rings. Preliminary tests confirmed that ring sticking could be further accelerated by reducing the side clearance of these parallel-sided rings in their grooves to 0·0015 inch, which was the smallest possible consistent with avoiding ring trapping arising from dimensional changes of the pistons.

With these modifications it was found that, with the good quality plain

oils, severe ring sticking would occur within 50 hours, under the following operating conditions :—

Full load at	1700 r.p.m. ± 20
Jacket coolant outlet temp	99° C ± 1°
Sump oil temp	110° C ± 1°

Under these conditions the following average values were obtained :—

B.m.e.p.	97·5 p.s.i.
Power output	125 b.h.p.
Specific fuel consumption	0·38 lb/b.h.p.-hr
Fuel input	84 cu. mm/cycle

Blow-by was usually 0·4 cu. ft/min at the start of test, but slight variations between tests did occur.

In order to maintain reproducibility, the following tolerances were adhered to throughout the series of tests :—

Piston skirt clearance (bottom)	0·007 inch	$\begin{cases} + 0{\cdot}001 \\ - 0{\cdot}000 \end{cases}$
Compression ring groove width	0·1250 inch	$\begin{cases} + 0{\cdot}0002 \\ - 0{\cdot}0002 \end{cases}$
Compression ring width	0·1235 inch	$\begin{cases} + 0{\cdot}0000 \\ - 0{\cdot}0002 \end{cases}$
Scraper ring groove width	0·2525 inch	$\begin{cases} + 0{\cdot}001 \\ - 0{\cdot}000 \end{cases}$
Scraper ring width	0·2485 inch	$\begin{cases} + 0{\cdot}0000 \\ - 0{\cdot}0005 \end{cases}$
Compression ring, load to close	4·5 lb	± 0·5
Scraper ring, load to close	7·7 lb	± 0·5
Compression ring gap	0·027 inch	$\begin{cases} + 0{\cdot}003 \\ - 0{\cdot}002 \end{cases}$
Scraper ring gap	0·025 inch	$\begin{cases} + 0{\cdot}003 \\ - 0{\cdot}002 \end{cases}$

Preparation of Engine for Test

After every test the engine was stripped, with the exception of the fuel pump and valves, all parts being marked to ensure reassembly in the same position. After inspection of the deposits, components to be used again were carefully cleaned. Owing to its size, the crankcase presented some difficulty, but a high pressure spray gun, using petrol, proved to be a satisfactory cleaning method. Other components were degreased or washed in petrol. Lacquer on the cylinder walls was removed by using a CRC approved cleaning solution in conjunction with a rotating bristle brush.

A complete set of new pistons and rings was fitted for every test. The wear, or other deterioration, of components likely to have a bearing on the consistency of engine behaviour, *e.g.*, cylinder liners, big-end bearings, was negligible over many hundred hours running, and throughout the whole series of tests it was only necessary to replace an occasional cylinder liner due to cracking at the upper locating lip. Particular attention was given to the injectors, which were cleaned and checked before fitting. Records of their performance on the test rig were kept, and if any slight deterioration was noted the injector was serviced before a defect developed.

The oil filter cloth was renewed for each test.

Test Routine

The test was a non-stop run of 50 hours duration, excluding " warming-up " time. If it became impossible to maintain steady operating conditions, due to excessive blow-by, the test was stopped short of 50 hours.

Prior to each test the engine was run-in to a schedule covering a period of 3½ hours, during which the load and speed were raised alternately every 15 minutes; the final ½ hour was at full load to ensure that the power output and blow-by were normal. During running-in, the jacket temperature did not exceed 70° C and the oil used was the same type as for the ensuing test. At the end of the running-in period the oil system, including the filter and cooler, was drained immediately after stopping and then refilled with 6 gal of fresh oil for the test.

On starting the test, the engine was brought up to test conditions slowly over a period of 1 hour, to avoid high loadings whilst the oil was cold. At the end of a test the engine was shut down slowly to avoid sudden cooling of the pistons. The sump was "topped-up" whilst running by adding ½ gal of oil when required, the amount normally consumed during a 50-hour test being of the order of 2½ gal.

During tests, oil and coolant temperatures and speed were under continuous close control and observations made, at not more than half-hourly intervals, of engine load, fuel consumption, oil pressures, exhaust smoke density, and blow-by. The last consisted of both the total blow-by from the start of test and the average rate as determined by timing the passage of 1 cu. ft. A chart was kept during tests of these blow-by readings, b.h.p., and exhaust smoke density.

Criteria of Oil Performance

After the above procedure and running conditions had been established to fail plain oils, it was found possible to discriminate generally between the plain and additive oils on the basis of ring sticking and blow-by characteristics.

The most important criterion of oil performance was the condition of the rings in their grooves as ascertained by inspection at the end of a test. An oil was considered to have failed the test if any rings were found to be "hot-stuck," *i.e.*, a ring stuck in its groove, with dark deposits on its working face showing that it had been stuck whilst running.

In addition, observation of rate of blow-by whilst running provided a valuable indication of performance for use in those cases where it was difficult to decide whether or not a ring had been stuck whilst running, as there may not be sufficient time in a short test for deposits to accumulate on the working face. Fig 1 shows typical examples of the two blow-by characteristics—rate and total—observed during these tests. A distinct difference is readily apparent between these two particular oils from about 23 hours onwards, and the subsequent experiments showed that these characteristics could be relied upon to give an initial indication of success or failure of an oil. In the case of the additive oil, the blow-by rate remains substantially constant, indicating that the rings are functioning correctly throughout the whole 50-hour period. In the case of the plain oil the blow-by rate, initially steady, becomes and remains irregular and increases considerably, indicating defective ring operation for the remainder of the test. The engine power is not affected to a measurable extent, and therefore cannot be used as a measure of oil performance.

In order to utilize blow-by rate as one of the criteria of oil performance it was decided, on the evidence of several tests, that if the blow-by rate

became irregular, increased to double its previous average value within the space of ½ hour, or less, then some of the rings were stuck, at least temporarily, and the oil was clearly unsatisfactory.

A further criterion was, however, necessary for oils which did not fail so catastrophically, but might nevertheless be unsuitable because of increasingly sluggish ring action, as evidenced by a slow departure from

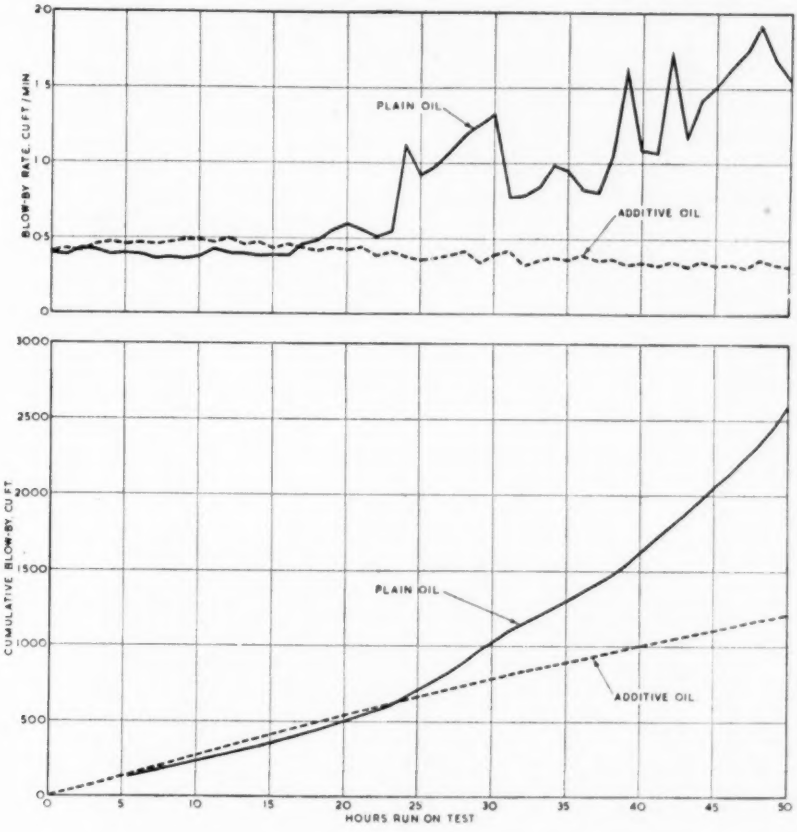

FIG 1

TYPICAL EXAMPLES OF THE TWO KINDS OF BLOW-BY TOTAL AND RATE CHARACTERISTICS

linearity of the cumulative blow-by graph. On the basis of several tests, it was decided that appreciable departure from steady blow-by indicated that the oil in question was not satisfactory, and a simple means of assessing the permissible deviation from a constant slope was to compare ten times the 5-hour blow-by total with the total at 50 hours. It was considered that the total at 5 hours was typical of the initial normal behaviour of each engine assembly. This method of denoting sustained increase in blow-by rate did not take into account the slight falling off in blow-by rate which

normally took place due to bedding-in of the rings. In those cases where an increase did occur, the 50-hour total was appreciably in excess of ten times the 5-hour total.

To sum up, an oil was deemed to have failed the test if :—

(1) There are any compression rings hot-stuck at the end of 50 hours running; or

(2) The blow-by rate should double its previous average value within the space of ½ hour; or

(3) The blow-by cumulative total appreciably surpasses ten times the total at 5 hours, before, or at, the completion of 50 hours running.

Results and Discussion

Table I contains details and results of the tests carried out; these may be divided into three groups :—

TABLE I

Results of Tests

Test no.	Test oil	Concentration of additive	Sulphur content of fuel	No. of stuck compression rings	Time at which blow-by rate became irregular, hr	Time at which blow-by total surpassed ten times 5-hr total, hr
1	A	—	Low	1	24	34
2	A	—	Low	0	30	47
3	A1	Normal	Low	0	—	—
4	A2	Normal	Low	0	—	—
5	A2	Normal	Low	0	—	—
6	A3	Normal	Low	0	—	—
7*	B	—	Low	5	18	—
8	B	—	Low	2	19	40
9	B1	Normal	Low	0	—	—
10	B2	Normal	Low	0	—	—
11	B3	Normal	Low	0	—	—
12	A1	Half	Low	0	—	—
13	A2	Half	Low	0	—	—
14	A	—	High	5	10	24
15	A1	Normal	High	0	46	—
16	A2	Normal	High	0	—	—
17†	B	—	High	7	16	31
18	B2	Normal	High	0	—	—
19	B2	Normal	High	0	—	—

* Test stopped at 35 hr. † Test stopped at 38 hr.

(1) tests 1 to 11, all oils tested using the low-sulphur fuel, together with repeats on several representative oils;

(2) tests 12 and 13, two additive oils, having only half the concentration of additive previously used, tested with low-sulphur fuel;

(3) tests 14 to 19, a representative selection of oils tested using the high-sulphur fuel.

Considering first of all the tests (1 to 13) using low-sulphur fuel, it will be seen that both the plain oils fail and all the additive oils (both normal

Fig 2

LABORATORY TEST PISTON

Plain oil. Low-sulphur fuel

Fig 3

LABORATORY TEST PISTON

Additive oil. Low-sulphur fuel

FIG. 4
LABORATORY TEST PISTON
Plain oil. High-sulphur fuel

FIG. 5
LABORATORY TEST PISTON
Additive oil. High-sulphur fuel

FIG. 6
EXAMPLE OF OPERATOR'S PISTON USING PLAIN OIL

and half strength) pass the test. In test 7 the blow-by total would have easily exceeded ten times the 5-hour total before 50 hours but for the fact that the test was stopped at 35 hours. This was an early test in the series, and was stopped when it was thought, by reference to the blow-by rate characteristic, that the oil had failed. However, in later tests the policy was adopted of running, when possible, for the full 50 hours, as it was thought desirable to base the other two criteria (of stuck rings and blow-by total) on a fixed period of running. Tests 2, 5, and 8 were repeat tests, and showed that the procedure repeated well enough for the purpose of a " go " or " not-go " test.

As a matter of interest, two tests (12 and 13) were carried out on oils, A1 and A2, with the additive concentration reduced to half that normally used in this series. As these oils passed the test, it can be concluded that under these conditions even half concentration additive oils are substantially better than plain oils, at least with low-sulphur fuel. However, it is not possible to say how half concentration oils compare with those of full concentration.

Turning now to tests 14 to 19, run on the high-sulphur fuel, it will be seen that the two plain oils, A and B, and the additive oil A1 failed the test, whilst additive oils A2 and B2 passed the test. During test 17, it was not possible to run the engine after 38 hours because of excessive blow-by. Test 19 was a repeat of 18, using oil drawn from the stock of the operator concerned; it was carried out to verify that the stock of oil used by the operator gave the same result in the laboratory engine as did the similarly marked stock supplied direct to MIRA.

The deleterious effect of the greater sulphur content of the fuel used in this group of tests is shown up not only by the failure of the additive oil A1, but also, qualitatively, by the generally dirtier appearance of the pistons when run on the high-sulphur fuel than when run on the low-sulphur fuel. This difference in piston appearance arising from the sulphur content of the fuel, together with the effect of the additives in keeping the piston clean, is shown up well in Figs 2, 3, 4, and 5, which are photographs of typical pistons after tests on plain and additive oils, using low- and high-sulphur fuels.

The outstanding feature of pistons from tests in which the oil failed was that the ring sticking occurred from the top compression ring downwards. The skirts of such pistons were covered with hard, tenacious lacquer, and there was considerable scratching of the top lands. In no case was the scraper ring affected in any way; it was always clean and free in its groove.

The rapidity with which the oil filter fouled during tests varied with the type of oil used, irrespective of the fuel. In the case of plain oils the pressure drop across the filter reached a maximum steady value after approximately 16 hours running, at which time it was assumed that the by-pass valve had come into operation. In the case of the additive oils the corresponding time was 32 hours.

Results of Caterpillar L.1 Tests

The same range of oils was tested in the laboratories of certain oil companies according to the CRC L.1, Caterpillar, single-cylinder engine test procedure using low-sulphur fuel. All the additive oils were rated better

than the two plain oils, and so the Caterpillar test agreed with the MIRA test in distinguishing between the plain and the additive oils.

Road Service Results

The service tests were run concurrently with the laboratory work and were carried out by two of the largest companies in the U.K. operating short stage bus services. Between them these two companies conducted extended service tests on all the oils used in the laboratory work. In carrying out the tests the operators made use of their respective normal maintenance routines. No reclaimed oil was used.

Tests by Operator A

This operator who had previously conducted tests using additive oils on a limited scale with promising results, organized large-scale tests on the plain oil A and the additive oils A1, A2, and A3. The largest and most effectively controlled test comprised 484 engines running on additive oils and 1243 engines lubricated with plain oils, all engines being of the 8-litre class. This operator set no mileage life for engines, the maintenance procedure being to change the engine when required. Hence comparisons could be made on an increase in average life and errors arising from the assessment of the condition of individual engines avoided. A special statistical technique had been developed for examination of engine life figures in which account was taken not only of engines that had failed but those still surviving when the test was brought to a conclusion.

The results showed that an increase in engine life of 8 per cent was obtained when using additive oils. These tests did not distinguish between one additive and another.

During these tests the sulphur content of the fuel was increasing, and for the concluding period it averaged 0·70 per cent, individual deliveries having a content as high as 1·0 and 1·06 per cent.

Tests by Operator B

Tests were carried out on forty-five 8-litre engines, of four different types, eleven using plain oil and thirty-four using additive oils. The additive oils were divided between three groups of engines in order that their performance could be assessed separately. This operator's maintenance scheme embodied an engine life between overhauls of 140,000 miles, with piston replacement at 70,000 miles. Not all the engines completed the major overhaul mileage within the time allotted for testing, and the results were judged on the condition at the first piston change.

The factors used in assessing engine condition were: (*a*) bore wear, (*b*) ring sticking, (*c*) lubricating oil consumption, and (*d*) top ring groove wear. On these bases the operator found that none of the additive oils showed any advantage over the plain oil. The data from engines reaching the overhaul period did not conflict with this conclusion.

Comparison of Results

The foregoing description of tests and results reveals disagreement between the laboratory and the service results. In summing up it can be said :—

(1) Operator A found a small improvement in engine life with the use of additive oils;

(2) Operator B found no improvement in engine condition with the use of additive oils;

(3) the laboratory tests showed a clear improvement in piston and compression ring condition with the use of additive oils with both low- and high-sulphur fuels; and

(4) the Caterpillar test procedure rated all the additive oils better than both the plain oils.

In the case of the laboratory pistons run with an oil which failed, the compression rings (or most of them) were stuck in their grooves, whilst the scraper rings were invariably free and clean. In the case of a failure in the service tests, the compression rings were sometimes stuck, but the scraper rings were almost always completely packed with hard baked deposits. In other words, failures in the case of the laboratory and road work were characterized by stuck compression rings and plugged scraper rings respectively. This difference can be seen by comparing the service piston in Fig 6 with the laboratory pistons in Figs 2 and 4. In addition, the laboratory pistons showed more hard adhesive deposits and lacquer on the lands and skirts and less soft soot deposits than the road pistons.

With reference to the difference between the experience of the two operators, it should be noted that, as well as possible differences in routes and schedules, differences exist in maintenance routines between the two. With a routine such as Operator B's (scheduled periods between overhauls) it would be more difficult to assess a slight change in oil performance.

Test Requirements of British Road Operation

Consideration of these differences and of this lack of correlation led to consideration of the whole question of different types of service in the U.K. and to their test requirements, judged by the condition of the engines upon stripping as well as the conditions of service under which the engines are run.

Operation of compression-ignition-engined road vehicles in the U.K. may be classified into three main types of service according to the terrain involved, the average speed of the vehicles, and the proportion of idling time :—

(1) long distance goods and passenger carrying service;
(2) local, intermittent operation in undulating districts;
(3) local, intermittent operation in hilly districts.

Engines from each type of service have been examined, and operators engaged in each type have been approached in an attempt to assess the differences existing between the types of service, and hence the test requirements of road vehicles in general.

Long-distance goods and passenger carrying service, not being localized, must necessarily cover a variety of terrains, and hence does not involve either frequent and prolonged, full-throttle, slow labouring uphill or fast, part-throttle running downhill. In addition, the operating schedules result in little idling of the engine. The vehicles are, therefore, for most of

the time running at part throttle at the designed cruising speed when it should be easy to ensure correct cooling of the engine. The result is that piston temperatures are probably consistently moderate, and the conditions of operation as near ideal as possible. Provided therefore that such engines are properly maintained, troubles attributable to the performance of the lubricating oil should be only rarely encountered. Visits to operators of this type of service have borne out this conclusion. Three operators of home and continental coach tours and four operators in the home counties of inter-urban passenger services stated that they suffer from no urgent lubrication problems. One operator of a cross-country goods haulage service stated that he "never encounters a stuck compression ring or plugged scraper ring." In all these cases the maintenance routines were quite normal, and the vehicles standard in every respect.

The second type of service, local, intermittent operation in undulating districts, is exemplified by the service tests described at length in this paper. It is a service characterized by a high proportion of alternate idling and full-throttle accelerating. By definition, there is little prolonged hill climbing. The typical lubricating oil failure in this service is the plugged scraper ring as described earlier. A visit to the operator of a service of this type in the Home Counties confirmed the observations made during visits to the two operators whose service tests were described in this paper. An extreme example, although not a numerically large one, of this type of service is provided by dust-collecting vans moving slowly from house to house, and idling most of the time. In one van operated in a Home Counties borough, and recently inspected, there was no lacquer or varnish on the pistons, compression ring grooves were 100 per cent packed with carbon, the scraper rings were plugged and completely out of action, and there was heavy bore wear. This vehicle had travelled 16,000 miles in 5000 hours. The operator held the condition of this engine to be typical of those from this service.

In the third type of service, namely, local, intermittent operation in hilly districts, the proportion of prolonged full-throttle, slow running uphill may be considerable, and hence high piston temperatures may be reached and maintained. However, there will be an equal mileage of light running downhill included in the schedule, together with idling at scheduled stops. In connexion with this type of service, visits were paid to the municipal transport departments of four towns in the Midlands and North of England, selected because they are situated in hilly districts. Their selection was confirmed by the severe brake lining wear values obtaining. In three cases compression ring sticking was considered to be more of a problem than scraper ring plugging, and in the fourth case, the two troubles were accorded equal importance. In no case, however, was either trouble regarded as really serious.

It would thus appear that among road vehicles in the U.K. there are few, if any, running under conditions comparable to those of the test procedure described in this paper, *i.e.*, in no type of British service is compression ring sticking the major problem. With reduction in idling time or increase in proportion of running time during which piston temperatures are high, there is a trend away from plugged scraper rings and towards stuck compression rings. But from the numerical point of view, scraper ring plugging

is by far the more important problem, and is therefore the one which is in most urgent need of investigation in the laboratory.

Conclusions

It is evident that the test procedures so far examined, although clearly differentiating between oils usually assumed to give widely differing engine performance, cannot be regarded as satisfactory for substantial numbers of compression-ignition-engined road vehicles in the U.K. It is, however, recognized that, even in the U.K., service conditions may vary considerably and that one type of test procedure may not satisfy all service requirements. As a result of the examination of the many engines from different types of service which has been made since the failure to obtain correlation between the laboratory tests described in this paper and short stage P.S.V. operation, it seems that there is a case for a test procedure involving, amongst other changes appreciably lower oil and coolant temperatures than have so far been used. Further work is now in progress along these lines.

THE CATERPILLAR L.1 AND CHEVROLET L.4 TEST PROCEDURES

By J. C. Cree *

Introduction

Over a period of several years preceding the second world war engine manufacturers in the U.S.A., notably the Caterpillar Tractor Co. and the General Motors Corporation, developed engine tests to determine the performance of lubricating oils under particular types of duty before recommending them for use in their engines. Also during this period a great deal of co-operative work was carried out between the above-mentioned companies, additive manufacturers, and lubricating oil producers, which brought these engine tests into fairly wide use for evaluating the performance of the newly developed additive-type, or heavy-duty lubricating oils.

By 1940 many oil companies in the U.S. were marketing H.D. oils [1] which were generally found to give superior performance to straight mineral oils in spark ignition and compression ignition engines, and which in consequence became widely recommended by engine manufacturers and oil companies for use in vehicles operated under fairly arduous conditions.

In view of these developments the U.S. Army Ordnance Department requested the Co-ordinating Research Council [2] to standardize a series of engine test procedures which could be used to qualify H.D. oils for use by the U.S. Army Ground Force vehicles.

The five test procedures selected by the CRC were those developed by

* Anglo-Iranian Oil Co. Ltd.

the Caterpillar Tractor Co. and General Motors Corp., which were formally published as standard engine test procedure under CRC designations L.1 to L.5 and specified as approval tests in the U.S. Army Ordnance Specification 2-104B.

When the U.S. entered the war they became the main suppliers of lubricating oil to the Allied armed forces and, in the interests of standardization of materials and equipment, H.D. oils meeting 2-104B requirements were eventually specified for use in the majority of ground vehicles in the Allied Forces.

The outcome of the wide distribution of these oils outside the U.S. was that by 1945 many engine builders and fleet operators, both in the U.K. and on the Continent, began to specify 2-104B quality oils for use in their vehicles. Furthermore, due to their guaranteed engine performance with respect to the CRC L-series of tests, 2-104B approval became the yardstick by which H.D. oils were judged.

In 1950 the 2-104B specification was replaced by the U.S. Ordnance Department Specification MIL-0-2104 (Ord.).[3] Only two of the original CRC tests were retained, the Caterpillar L.1 and the Chevrolet L.4, but the essential details of these two tests with respect to operating conditions remained unchanged. However, a raising of the quality level of oils approved under MIL-0-2104, in terms of detergency as shown by the L.1 test, was effected by specifying a fuel designed to increase piston deposits and demanding a higher level of piston cleanliness than was previously required under the 2-104B specification.

This increase in the quality level of the oils required for military purposes brought about by the adoption of the MIL-0-2104 specification had its repercussions in civilian markets, and resulted in a corresponding increase in the quality level of H.D. oils specified by engine builders and users. Once again the explanation appears to be, apart from the better performance obtainable with MIL-0-2104 oils, that oils known to meet this specification were of a guaranteed engine performance.

More recently the British Ministry of Supply has published a specification[4] designated DEF/2101 which forms the British equivalent of the American MIL-0-2104 specification; the engine tests, method of approving oils, and the quality level required for DEF/2101 approval are for all intents and purposes identical.

Both these specifications are intended solely for maintaining a standard of lubricating oil quality for American and British Armed Forces, and the importance they have attained in commercial fields is purely incidental. MIL-0-2104 approved oils, and also, it is believed, DEF/2101 approved oils, must not, under the terms of the approval, be advertised or branded with an approval number when supplied to civilian markets.

The BSI published in December 1952 a specification,[5] BS 1905 : 1952, which is practically identical in all respects with the MIL-0-2104 and DEF/2101 specifications. The stated purpose of this specification is "to safeguard the standard of supplies for those users who are convinced they secure sufficient benefits from this type of lubricating oil (heavy duty), and to define the nature of oils for those who wish to establish their field of usefulness."

From the foregoing brief survey of the way in which Caterpillar CRC L.1

and Chevrolet L.4 test procedures have been incorporated in specifications relating to H.D. oils it will be seen that these tests are widely used and play a big part in the quality control of high quality oils. The IP, through the activities of the Engine Tests of Lubricants Panel [6] set up in 1944 to consider engine tests for lubricants, has been concerned with the operation of these test procedures in the U.K. from the standpoint of specifying them as standard methods of test; and a considerable amount of co-operative work has been carried out between the companies and organizations represented on this panel. The aims of this work have been to establish the repeatability and reproducibility of the tests, and to suggest and investigate developments which would improve these factors. On the recommendations of this Panel the CRC L.1 procedure was published [7] as an IP standard method IP 124/49, and the Chevrolet CRC L.4 procedure is to be similarly published later.

It is the main purpose of this paper to discuss some of the co-operative work which has been carried out, with a view to indicating the repeatability and reproducibility of results obtained by the L.1 and L.4 tests, and to show their usefulness as a means of controlling the quality of H.D. oils.

It must be emphasized, however, that any opinions expressed are those of the author, and are not necessarily shared by other members of the IP Engine Tests of Lubricants Panel.

The Caterpillar L.1 Procedure (IP 124/49)

The conditions under which the engine is operated may be considered to be equivalent to running an air-cell type, four-stroke compression ignition engine at a load and speed approaching the maximum rated values, for an engine of this type and size, for a period of 480 hours. The lubricating oil and jacket coolant temperatures specified for the test are in line with those which would normally be encountered under service conditions, and the procedure provides a means of evaluating the properties of lubricating oils with respect to ring sticking, piston and oil system deposits, and engine wear when used under fairly severe conditions of endurance.

The first single-cylinder Caterpillar lubricating oil test engines were introduced into the U.K. towards the end of world war II, and in 1945 a co-operative programme of L.1 tests on selected oils was carried out, under the auspices of the Engine Tests of Lubricants Panel, by the three laboratories who were then operating these engines. In all, five test oils were selected, and samples of these were distributed to the three laboratories concerned. Four of the oils were SAE 30 H.D. grades imported from the U.S. and reputed to have U.S. Ordnance Department 2-104B approval, while the fifth oil was a highly refined SAE 30 straight mineral lubricating oil.

Two of the laboratories tested all five of the oils, while the third was able only to test one of the H.D. oils and the straight mineral oil. The tests were made in accordance with the CRC L.1 procedure, and the results given numerical demerit rating using a rating system [8] which was later to form the basis of that published in the IP 124/49. The results of these tests are given in Table I.

TABLE I

Results of Caterpillar L.1 Tests on IP Reference Oils

Reference oil	IP 30			IP HD. 30–1							IP HD. 30–2		IP HD. 30–3		IP HD. 30–4	
Laboratory	A	B	C	A			B			C	A	B	A	B	A	B
				Demerit Ratings												
For cleanliness:																
Ring sticking	3·0	2·0	2·5	0·5	0	0	0	0	0	0	0	0	0	0	0	0
Piston skirt lacquer	3·5	3·0	3·3	0·4	0·1	0·1	0	0·2	0·1	0·2	0	0	0·2	0	0·3	0
Cylinder liner lacquer	0·3	0	0·2	0·1	0	0	0	0	0	0	0	0	0	0	0	0
Ring groove deposits (average)	3·6	3·6	5·1	2·8	2·7	1·3	1·3	1·2	1·8	1·3	2·0	0·4	2·4	1·9	3·4	2·3
Crown land deposits	2·1	1·5	1·5	1·0	1·5	1·8	3·0	2·4	2·0	1·5	2·2	1·9	1·6	2·0	1·4	1·2
Ring land deposits (average)	2·6	2·0	7·0	2·6	1·4	1·2	0·5	0·3	1·2	1·4	1·1	0·2	1·6	0·3	2·1	1·4
Oil system sludge deposits	5·4	6·0	2·8	2·4	2·2	2·0	2·0	2·0	1·6	0·8	1·0	0·5	2·0	0·6	2·8	0·6
Oil ring slot deposits	0·1	2·0	0·3	0	0	0	0·1	0·1	0·1	0·3	0·1	0·1	0	0·1	0	0·1
Oil groove hole deposits	0·1	2·0	0·3	0	0	0	0·1	0·1	0·1	0	0	0	0	0·1	0	0·1
Carbon cutting	6·1	4·8	4·5	3·1	2·2	1·6	3·8	2·8	3·8	4·0	3·1	4·9	3·5	4·0	3·9	6·2
Total cleanliness demerit	26·8	26·9	27·5	12·9	10·1	8·0	10·8	9·1	10·7	9·5	9·5	8·0	11·3	9·0	13·9	11·9
For wear:																
Cylinder liner wear	4·3	4·0	2·6	0·5	0·2	0·6	0·5	0·4	0·5	0·5	0·6	0·4	0	0·1	0·5	2·2
Top ring wear	2·9	3·5	1·9	0·8	1·7	1·0	0·9	1·0	0·9	0·5	1·3	0·8	0·7	0·5	1·8	2·9
Total wear demerit	7·2	7·5	4·5	1·3	1·9	1·6	1·4	1·4	1·4	1·0	1·9	1·2	0·7	0·6	2·3	5·1
Total demerit rating	34·0	34·4	32·0	14·2	12·0	9·6	12·2	10·5	12·1	10·5	11·4	9·2	12·0	9·6	16·2	17·0
Mean demerit rating on each test oil	33·5			11·6							10·3		10·8		16·6	

Comparing the demerit ratings assigned to individual items it will be seen that there were a few fairly wide differences, particularly between laboratories, but a subsequent exchange of views and comparison of some of the actual engine parts showed these were mainly due to differences in the interpretation of certain definitions given in the rating system. It was not possible to revise the ratings which had been assigned as only a limited number of the parts were available.

Nevertheless, accepting these differences the degree of correlation between both the total cleanliness demerits and total wear demerits obtained on all the oils was remarkably good, and showed the reproducibility of the test, as applied to oils of these two quality levels, to be very satisfactory. Similarly, the triplicate test carried out on IP H.D. 30–1 at laboratories "A" and "B," using one engine in each case, show the repeatability to be of the same order.

The total demerit ratings clearly demonstrate the suitability of this procedure for differentiating between H.D. and straight mineral oils. It should also be pointed out it was later established that the H.D. oils in this series were only "borderline" even by 2-104B standards, so it will be appreciated that the difference shown by this procedure between an average straight mineral oil and an average present-day H.D. oil meeting MIL-0-2104, or the DEF/2101 specification, would be considerably greater. In fact, a H.D. oil meeting these specifications and rated by the same method as the results given in Table I would have a total demerit rating of between 3·0 and 5·0, of which approximately 1·5 to 2·0 would be associated with the carbon cutting demerit.

While it is not intended in the scope of this paper to draw comparisons between service data and the results of tests made in accordance with standard test procedures, it should be mentioned that the London Transport Executive also co-operated in the programme of tests made on the IP reference oils. The conclusion [9] obtained from these service tests broadly confirmed the differences which were shown by the Caterpillar L.1 tests between the H.D. and straight mineral oil.

With the advent of the MIL-0-2104 specification, followed by the general raising of the quality level of H.D. oils, the criterion of L.1 test results became centred round the amount of carbon deposited in the top ring groove. Although the decision to pass or fail an oil submitted for MIL-0-2104, DEF/2101, or BS 1905/1952 rests solely with the relevant Approval Panel, it is generally accepted that a satisfactory H.D. oil tested by the Caterpillar L.1 procedure must give not more than the equivalent of 25 per cent carbon filling in the top piston ring groove, equivalent to a demerit of 2·5; not more than a trace of lacquer in the second ring groove and on the first ring land, less than a demerit of 0·1; and the remainder of the piston clean. For comparison with results given in Table I this would be equivalent to a combined average ring groove and ring land demerit rating of 0·6.

Coinciding with the commencement of the testing of heavy-duty oils designed to meet these requirements, a second Caterpillar test engine was installed at the Sunbury laboratory. It was found that this engine consistently gave less carbon packing behind the top piston ring groove than the original engine when operated on identical oils, approximately in

the ratio of 1 to 3; consequently it was possible to pass certain oils in one engine while these were rated as " fails " in the other.

In order to investigate the cause of this difference, a comprehensive programme was initiated in which pertinent component parts of the engines were interchanged, and as a result of a process of elimination it was found that the discrepancy was due to the difference in the lengths of the exhaust pipes between engine and expansion chamber.

Exhaust pressure diagrams, taken at a point close to the exhaust valve port, showed that in the engine which gave the higher top ring groove deposits the instantaneous pressure at a point in the cycle immediately before the exhaust valve closed was 1·2 p.s.i.g., whereas in the other engine the corresponding pressure was −0·6 p.s.i.g. In both engines the exhaust pressures measured by means of a manometer, as stipulated in the CRC L.1 procedure, were within the prescribed limits, and were respectively 0·8 and 0·5 inch Hg.

On fitting identical exhaust systems to the two units good agreement was obtained with respect to top ring groove carbon filling.

These findings were reported to the IP Engine Test of Lubricants Panel, and the work was continued on a co-operative basis. Exhaust pressure diagrams were obtained on all the Caterpillar test engines then in operation in the U.K., but unfortunately insufficient data were available on the relative severity of the engines investigated to arrive at definite conclusions regarding the effect of exhaust pressure on top ring groove deposits. However, it was shown that wide difference existed between various Caterpillar L.1 installations, and the probable severity of several engines, estimated from the work carried out at Sunbury, agreed with opinions which had previously been formed of these engines from a comparison of test results from other sources. A report of the work was prepared by the Panel and submitted by the IP to the CRC for further consideration.

The main conclusion stated in this report was that all the evidence which was available suggested that differences in piston deposits obtained using various Caterpillar test engine units were connected with differences in size and layout of the exhaust systems fitted to these units; but it was emphasized that insufficient work had been carried out to show whether or not reproducibility could be effected in all cases by eliminating differences in exhaust systems. The report also contained a recommendation that a standard exhaust system should be specified as part of the equipment necessary for carrying out standard L.1 tests, and, as a corollary, as part of any engine test procedure of a critical nature.

To conclude the review of L.1 procedure it is felt that the following points, based on the results of co-operative work and the author's personal experiences, should be emphasized :—

1. The L.1 procedure has proved itself to be a suitable means of evaluating the performance of heavy-duty oils for the purposes of quality control, but when used for conducting tests for specification purposes there are factors which are not sufficiently covered by the present procedure.

2. It has been found that the repeatability of top ring groove filling is ±10 per cent of the mean value of a number of tests on the same

oil, but the reproducibility may be as high as ±15 per cent even when identical exhaust systems are employed.

3. Lacquer deposits below the top piston ring groove may vary between zero and something which is considered more than a trace when certain oils are tested in two or more engines. The reason for this variation is not apparent, but it appears to be independent of the exhaust system used. It must, however, be added that differences experienced between engines in this respect are small and assume importance only when oils are being tested which are required to meet the stringent requirements of the MIL-0-2104, DEF/2101, and BS 1905/1952 specifications.

The Chevrolet L.4 Test Procedure

This test is carried out in a six-cylinder, four stroke, spark ignition automobile engine which is operated at a high oil sump temperature (280° F) and jacket coolant temperature (200° F). The duration of the test is 36 hours at an engine speed of 3150 r.p.m. (equivalent to vehicle travelling at 60 m.p.h.) and load of 30 b.h.p. For the purposes of the test a " Tocco " induction hardened crankshaft and copper–lead big-end bearings (two per test) are fitted, otherwise the standard parts specified for the normal production engine are used throughout.

Unlike the Caterpillar L.1 procedure, the Chevrolet L.4 test is an accelerated test, designed to evaluate oxidation characteristics of heavy duty oils intended for use in both spark ignition and compression ignition engines. After test the pistons and various other engine parts are rated for sludge and lacquer deposits, and the copper–lead bearings are assessed for corrosion by determining the weight loss.

Experience has shown that there is no correlation between deposit-forming properties of lubricating oils as shown by this procedure and those formed in a compression ignition engine. To take only one example to illustrate this point, the piston skirt lacquer merit ratings (10 = clean; 0 = completely covered with lacquer) obtained after L.4 tests on IP H.D. 30–1 and IP 30 reference oils were 6 and 9 respectively, whereas it has been shown previously, Table I, that when rated by the L.1 procedure the IP H.D. 30–1 was far superior to the IP 30 reference oil in all respects.

The inclusion of this test in specifications relating to H.D. oils intended for use in compression ignition engines is to determine the suitability of these oils preventing copper–lead bearing corrosion. While there is no direct evidence that L.4. copper–lead bearing results correlate with service data, the evidence which is usually given in its favour is that, before the test was used to check this property of compression ignition crankcase oils, copper–lead bearing corrosion was a problem in service, but since it was adopted as a standard test procedure there have been no complaints from the users of approved oils.

Before recommending this procedure as an IP Standard an investigation was instigated by the Engine Tests of Lubricants Panel into the reproducibility of the test. Five laboratories co-operated, and the reference oils specified in the CRC L.4 procedure for checking engine behaviour and fuel characteristics were used as the test oils. The quality of the three oils may be defined as follows :—

Reference Oil REO. 7.—An oil which passes the test in all respects.

Reference Oil REO. 8.—An oil which has borderline cleanliness properties and is poor in respect of bearing corrosion.

Reference Oil REO. 7/12.—An oil which gives satisfactory cleanliness ratings, but gives a high bearing weight loss.

All the tests were made with the same fuel and adhering strictly to the requirements of the CRC L.4 procedure.

Summaries of the results are tabulated in Tables II, III, and IV, a brief analysis of the results being :—

	Reference oil		
	REO. 7	REO. 8	REO. 7/12
Piston skirt lacquer ratings :			
Min–max	9·2–9·8	6·0–8·4	8·9–9·7
Average result	9·5	7·3	9·3
Standard deviation	0·21	0·81	0·25
Total sludge and lacquer ratings :			
Min–max	90·0–98·3	83·9–90·0	84·9–96·9
Average result	94·3	87·6	91·3
Standard deviation	2·7	2·7	3·7
Bearing weight losses, mg :			
Min–max	49–179	256–703	618–2399
Average result	93	466	1218
Standard deviation	33	136	532
Number of values	12	8	11

It will be noted from Tables II and IV that reference oils from two different batches were used, but there appears to be no significant difference between the batches, and this fact has been ignored in the above analysis.

It is evident that the reproducibility of the bearing weight loss rapidly deteriorates with increasing average bearing weight losses, and indicates that the L.4 procedure is of little value for comparing bearing weight losses of oils which give appreciable corrosion during the 36-hour test period.

TABLE III

Summary of Chevrolet L.4 Test Results on REO. 8 Reference Oil

Laboratory	A		C				D	E
Reference oil batch No.	REO.8/48		REO.8/45				REO.8/45	REO.8/45
Bearing wt loss (av per whole brg), mg	546	434	451	487	290	256	564	703
Piston skirt lacquer merit rating	8·2	8·4	6·4	6·9	7·8	7·8	7·0	6·0
Total sludge and lacquer merit rating	89·5	89·7	84·6	83·9	86·8	86·1	90·0	90·0

On the other hand, it is suitable for specification purposes if, as is believed to be the case with the MIL-0-2104 specification, a limit of 200 mg maximum weight loss is specified. This will then ensure that only oils giving little or no corrosion will be approved. Whether or not this figure is in line with service requirements is a debatable point, and the opinion has been expressed that even higher bearing weight losses, as determined by the

TABLE II

Summary of Chevrolet L.4 Test Results on REO.7 Reference Oil

Laboratory	A		B		C				D		E	
Reference oil batch No.	REO.7/45		REO.7/45	REO.7/48	REO.7/45				REO.7/45	REO.7/48	REO.7/45	REO.7/48
Bearing wt loss (av per whole brg), mg	74	49	115	78	97	113	64	74	80	86	179	102
Piston skirt lacquer merit rating	9·6	9·5	9·3	9·7	9·3	9·2	9·5	9·2	9·3	9·6	9·8	9·8
Total sludge and lacquer merit rating	94·9	93·8	97·1	97·2	90	92·9	91·6	91·9	91·8	94·4	97·8	98·3

TABLE IV

Summary of Chevrolet L.4 Test Results on REO. 7/12 Reference Oil

Laboratory	A		B		C				D	E	
Reference oil batch no.	REO.7/45 REO.12/46		REO.7/46 REO.12/48	REO.7/48 REO.12/48	REO.7/45 REO.12/46				REO.7/48 REO.12/48	REO.7/45 REO.12?	
Bearing wt loss (av per whole brg), mg	618	878	2399	1112	997	933	891	782	1103	1879	1812
Piston skirt lacquer merit rating	9·0	9·5	9·4	9·4	9·0	8·9	9·1	9·3	9·2	9·6	9·7
Total sludge and lacquer merit rating	91·3	90·8	96·9	94·9	85·6	84·9	90·8	88·3	93·5	96·1	91·2

L.4 procedure, could be tolerated in service without causing any adverse effects in vehicles using copper–lead bearings. This may or may not be true, but from the above results it is obvious that it would not be possible to apply a limit higher than 200 mg to the L.4 test results, as the extremely poor reproducibility would render the test impracticable for quality control.

It is believed that any bearing corrosion engine test would be unreliable unless it was applied merely to differentiate between oils which appreciably corroded bearings and those which do not. So many uncontrollable factors affect the rate at which a bearing corrodes once the induction period has been passed that reproducibility would almost certainly be poor.

The reproducibility of both piston skirt lacquer ratings and total sludge ratings was reasonably good, and it is of interest to note that the standard deviations calculated for these items, and for bearing weight loss, compare favourably with those relating to a similar series of tests carried out in the U.S. on the reproducibility of the Chevrolet L.4 procedure.

Inferences which may be drawn from the foregoing are summarized :—

1. The procedure satisfactorily reproduces piston skirt lacquer deposits and other engine lacquer and sludge deposits, but the practical value of these assessments is uncertain. As applied to the detergent properties of H.D. oils required for use in compression ignition engines the test serves no useful purpose.

2. The reproducibility of bearing weight losses, or corrosive properties, is poor when the procedure is used to test oils which perceptibly corrode copper–lead bearings under the conditions of this test and renders it impracticable for assessing degrees of corrosion.

3. The test does provide a means of controlling the quality of heavy duty oils with respect to copper–lead bearing corrosion when it is used on a "go-not-go" basis to differentiate between oils which give little or no corrosion and oils which corrode this type of bearing. Indirect evidence suggests that when so employed the results are applicable to both spark ignition and compression ignition engines.

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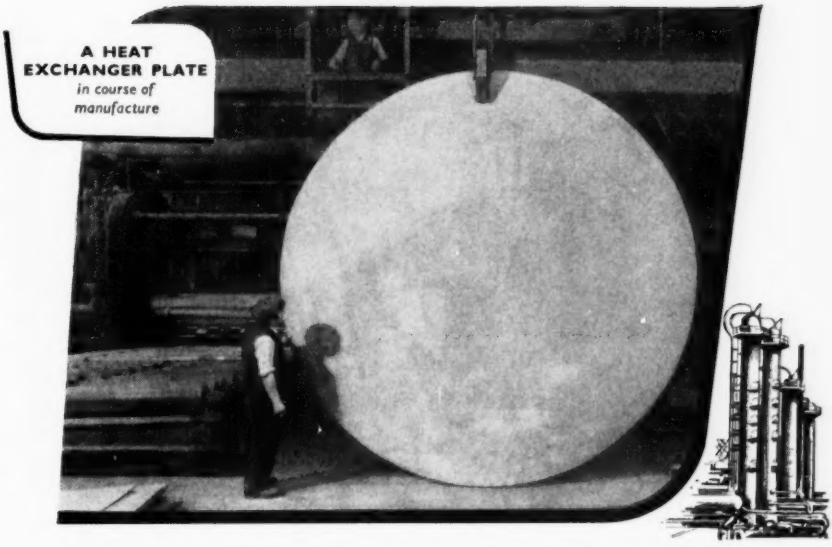

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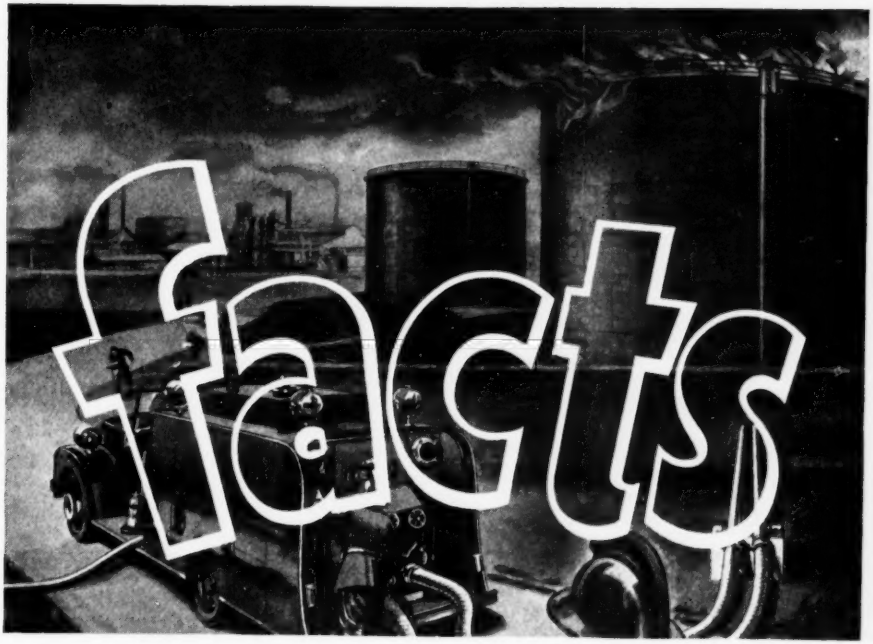

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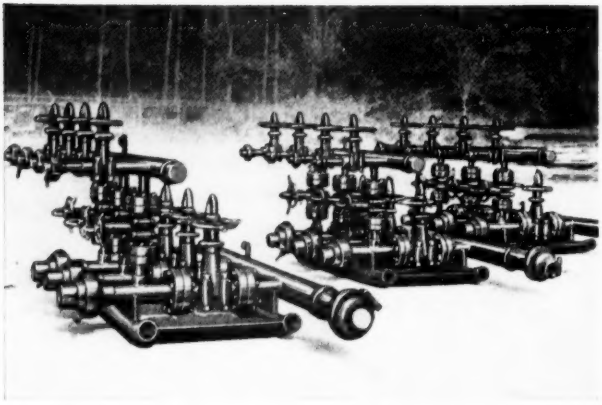

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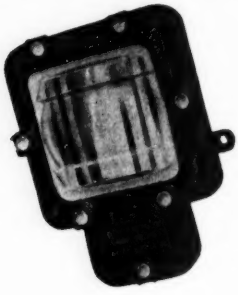

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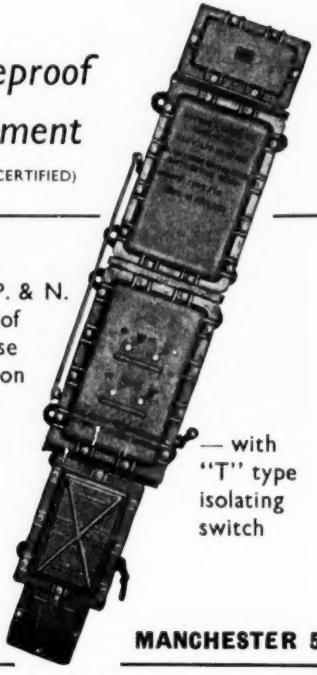

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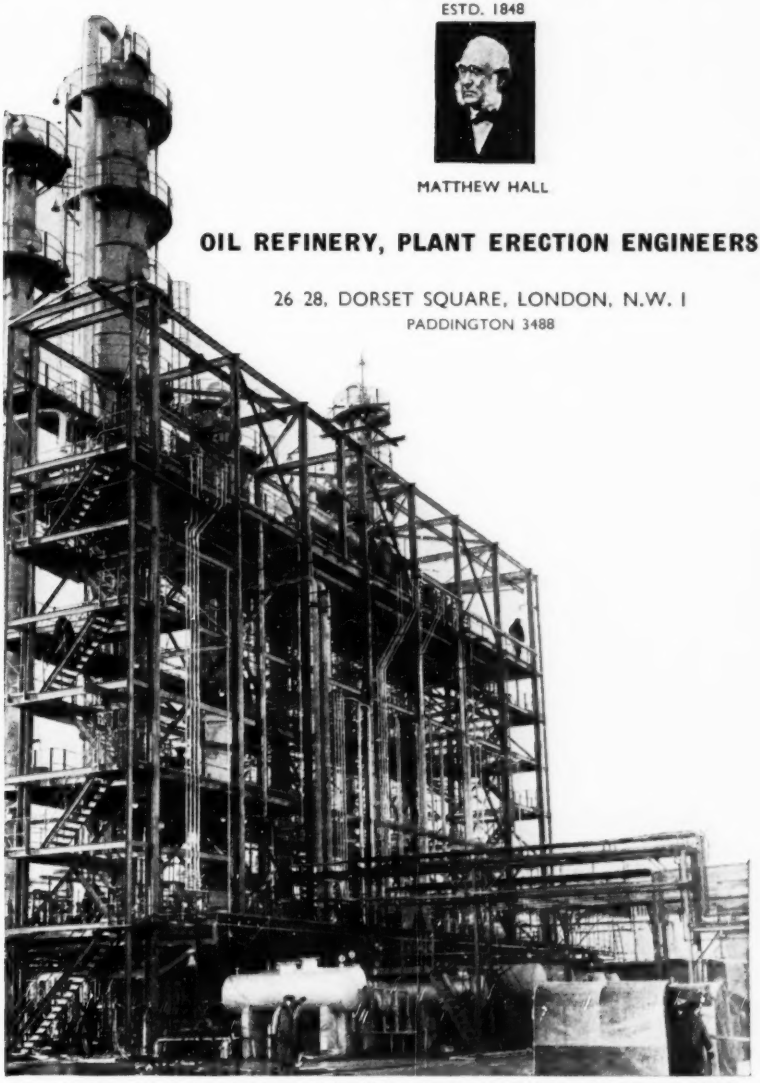

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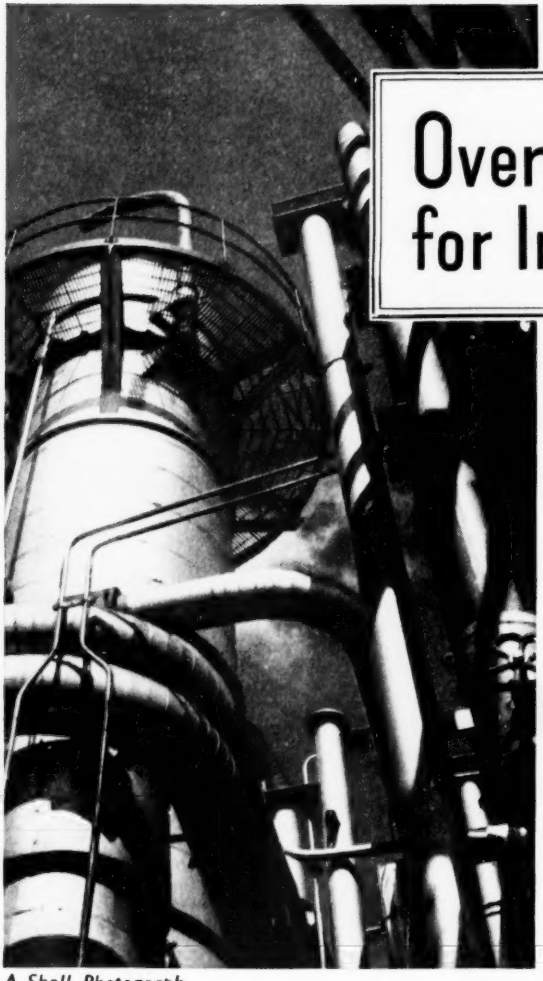

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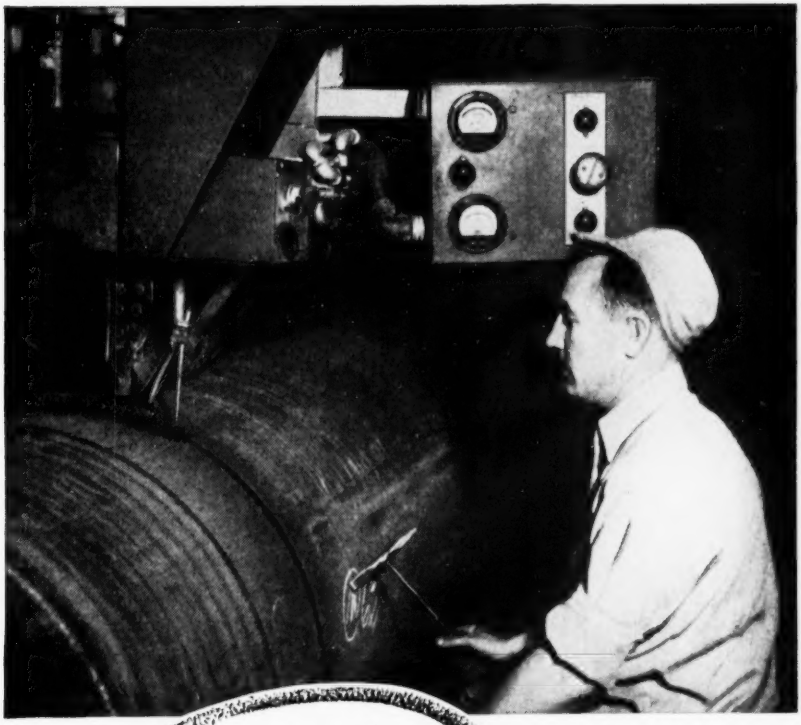

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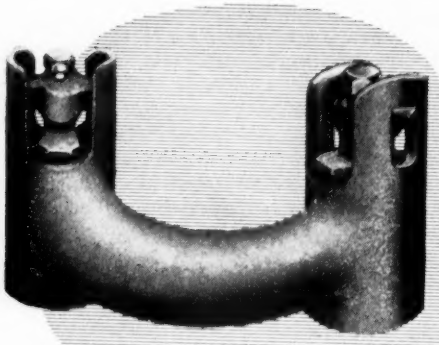

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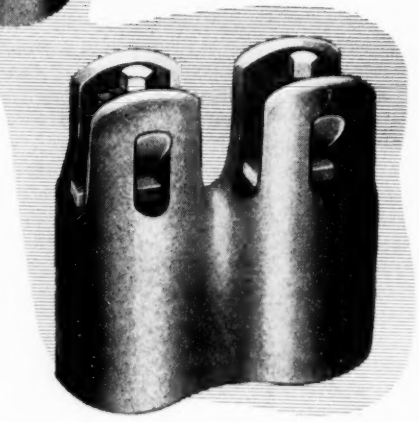

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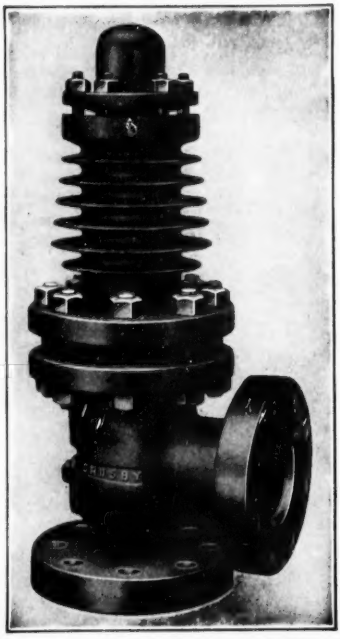

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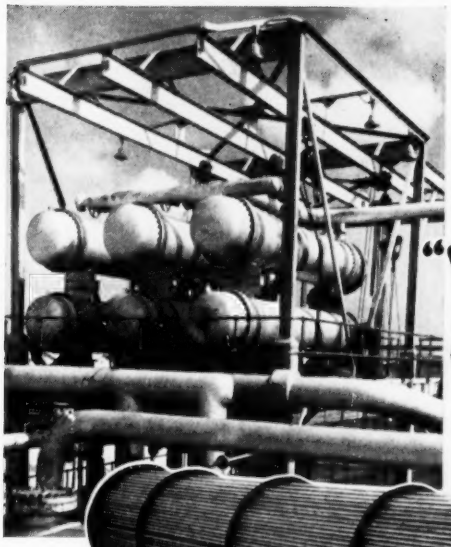

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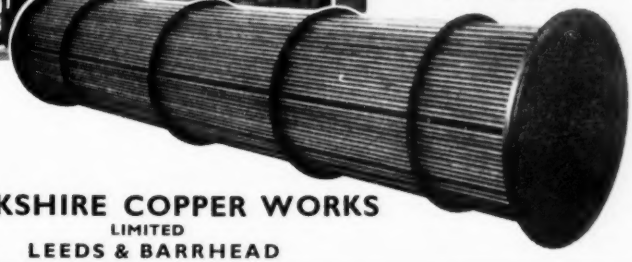

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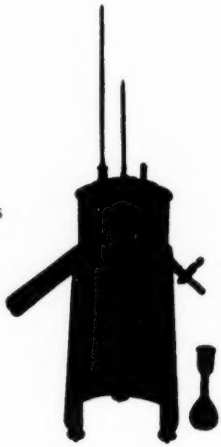

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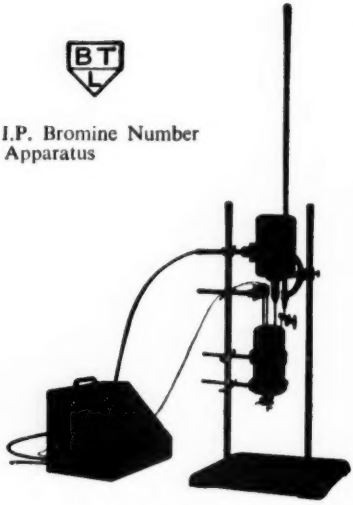

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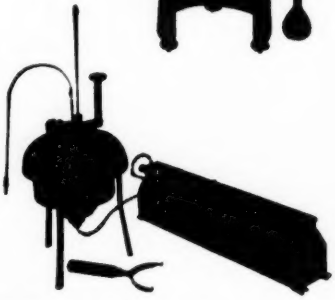

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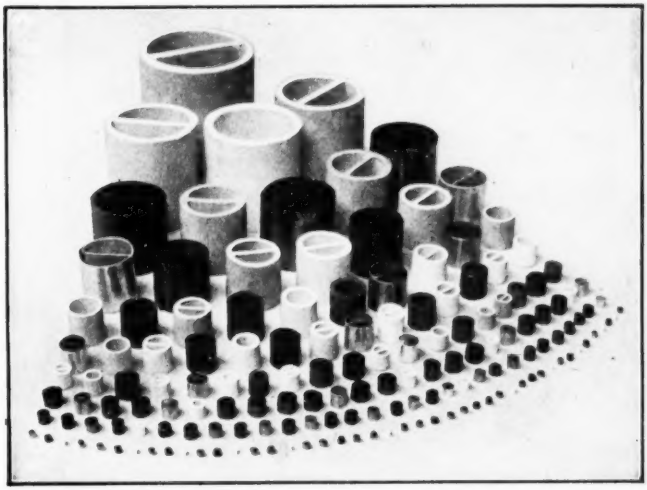

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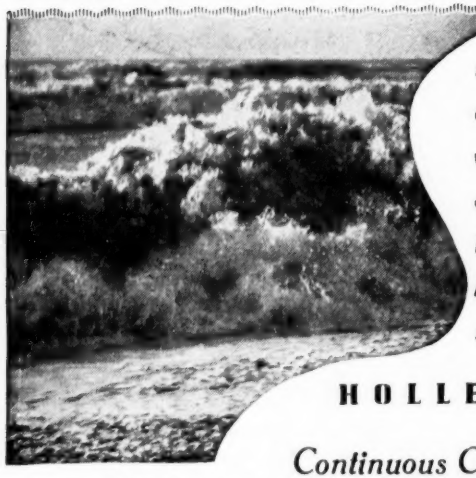

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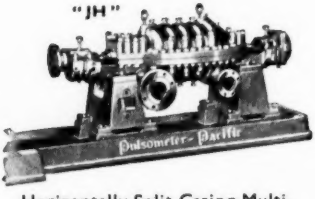

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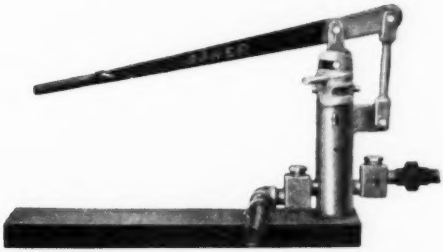

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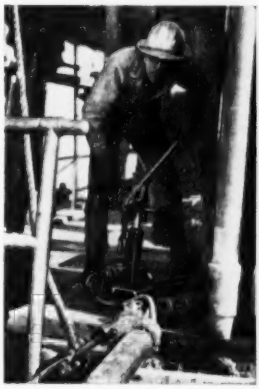

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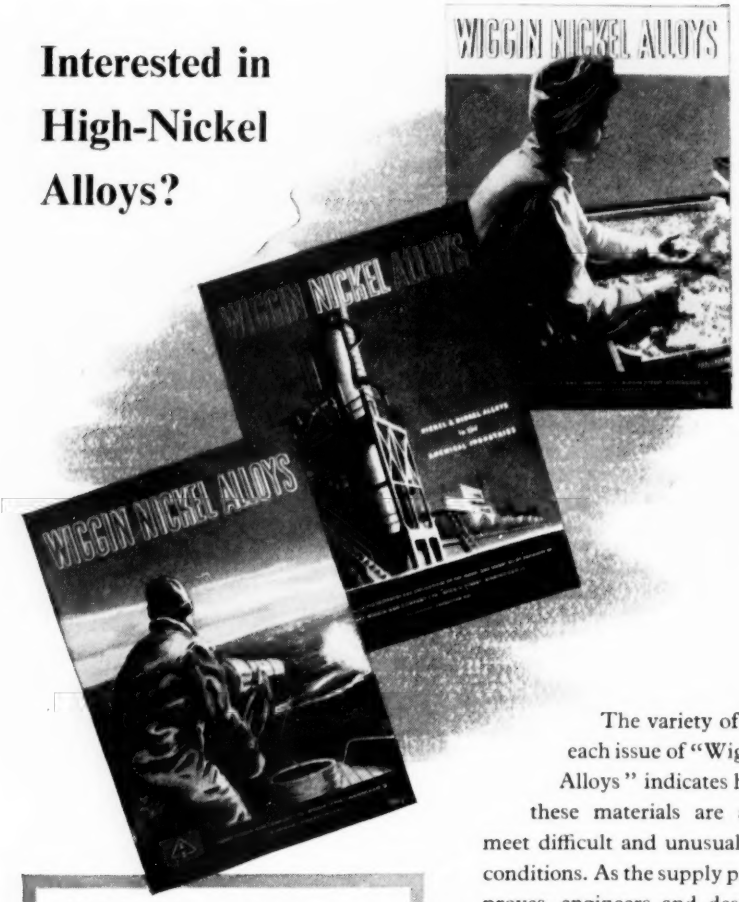

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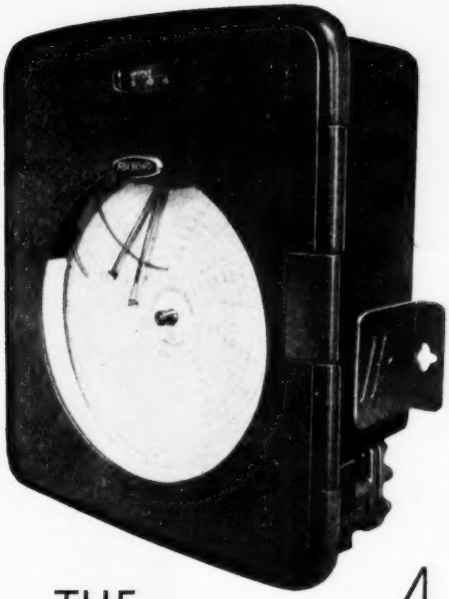

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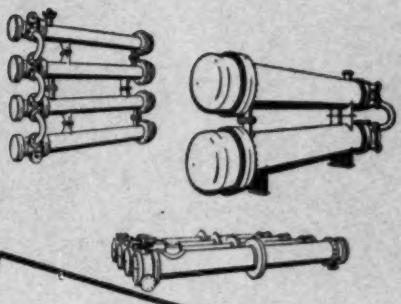

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